Computational Fluid Dynamic (CFD) simulation for continuous casting process of steels

A THESIS SUBMITTED IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Metallurgical and materials engineering

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May’2015

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CERTIFICATE

*This is to certify that the work in this thesis report entitled "***Computational Fluid Dynamic (CFD) simulation for continuous casting of steels"** *which is being submitted by* ***Mr. Rahul Kumar*** *(Roll no: 213MM1471) of Master of Technology, National Institute of Technology Rourkela, has been carried out under my supervision in partial fulfilment of the requirements for the degree of Master of Technology and is an original work. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.*

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Abstract

A comprehensive numerical simulation of flow behavior of molten steel as well as slag inside tundish and mold of continuous casting machine has been performed using Computational Fluid Dynamics (CFD). Modeling of continuous casting process of steels is very important as fluid flow behaviour inside tundish, sub-entry nozzle (SEN) and mold directly influence the quality of steel product. Investigations on inclusion entrapment and the chances of SEN clogging study during continuous casting process for steel are objectives of this thesis work. The outcrop of the developed mathematical model is beneficial to study effect of flow controller (e.g. dam and weir) putting inside tundish on the fluid flow behaviour throughout tundish, sub-entry nozzle (SEN) and mold of continuous casting machine. In addition to that, a massless particle is injected from the inlet and the trajectories of the particle inside tundish have been investigated using Discrete Phase Model (DPM) along with k-ε turbulence models. All the numerical simulation of fluid flow has been performed using ANSYS 15.0 software. This CFD simulation work demonstrates the correlation of flow controller's shape, size and position with inclusion flotation possibility and path in tundish. This work also elaborates and shows the significance of flow controller position inside tundish on fluid flow behaviour in tundish, sub-entry nozzle (SEN) and mold and quality of steel. The extract and underlying theory for this developed CFD model can be extended to different kinds of CCM process for various metal or metallic alloys to reveal the interrelation between inclusion removal kinetics and fluid flow behavior of molten steel and slag.

Keywords – continuous casting process, CFD, tundish, mold, SEN, Flow control devices

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Chapter – 1

Introduction

1.1. overview

In continuous casting process the hot liquid metal from ladle is poured into the tundish and from the tundish the liquid metal goes into the mould through the SEN, the first solidification starts in the mould at the metal/mould interface and from there the semi-solid material goes into the caster and with different cooling condition and rolling operations finally the liquid material is solidified and cut into different shapes such as blooms, billets. The Continuous Casting process starts from the tundish till the final solidified material is obtained and as the liquid metal is fed continuously from the tundish so it is called continuous casting process and is mainly used for casting the steel material.

The earlier process of making steels were Bessemer process and Siemens-martin process which turns steel making into a big industries. Now a day's steel can be prepared from any one of the two processes-

1) Basic oxygen steel(BOS) process-

   It uses oxygen to melt the material and uses liquid pig iron and scrap to produce steel

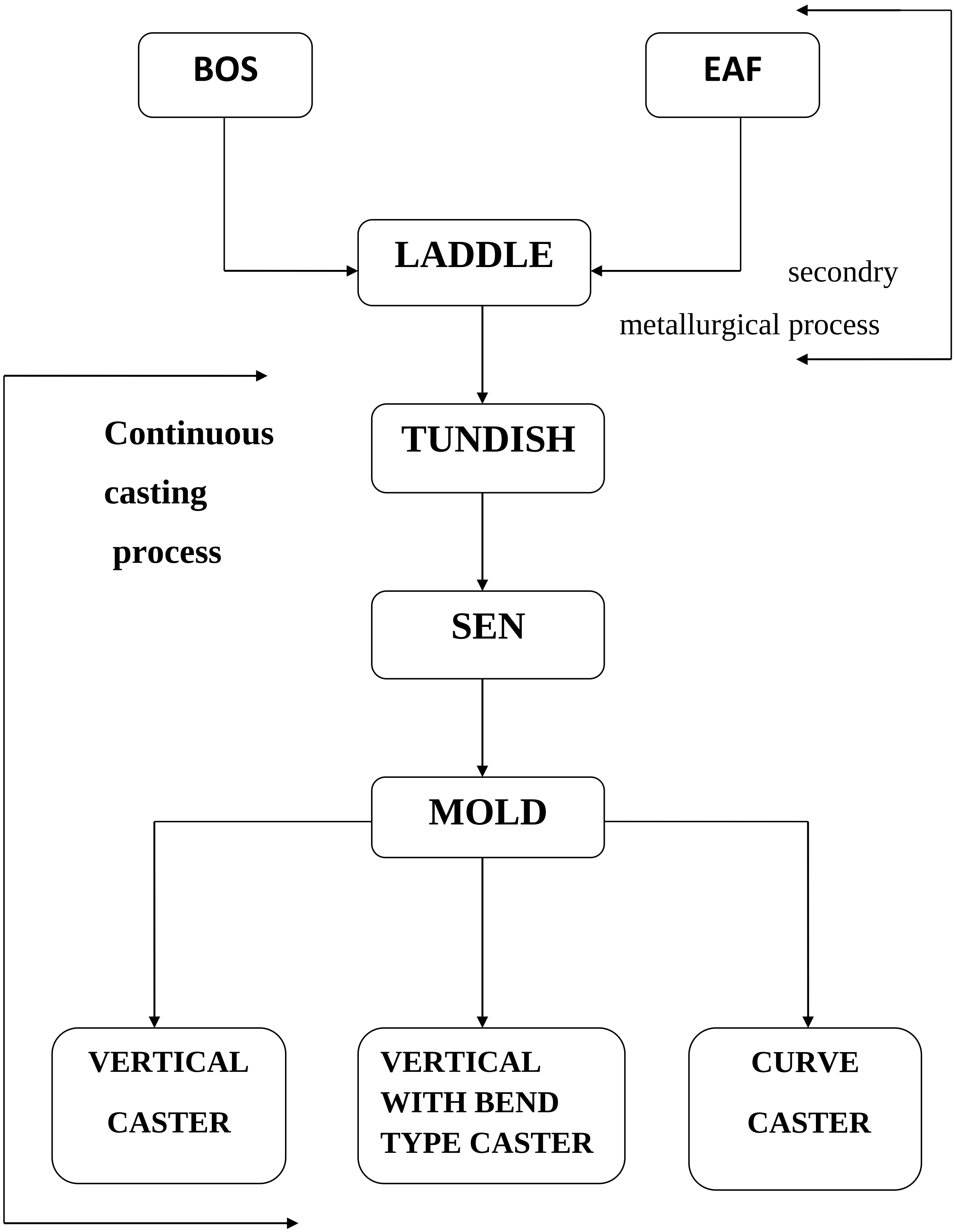
2) Electric arc furnace(EAF) process-

   It uses electric energy to melt the material and uses scrap as direct feed material

The liquid metal from the BOS or EAF is poured into the tundish through the ladle, from then it goes to several parts of CCP to finally get solidified. The various parts of continuous casting processes are-

1. Tundish
2. SEN
3. Mould
4. Caster

Flow chart of continuous casting process-



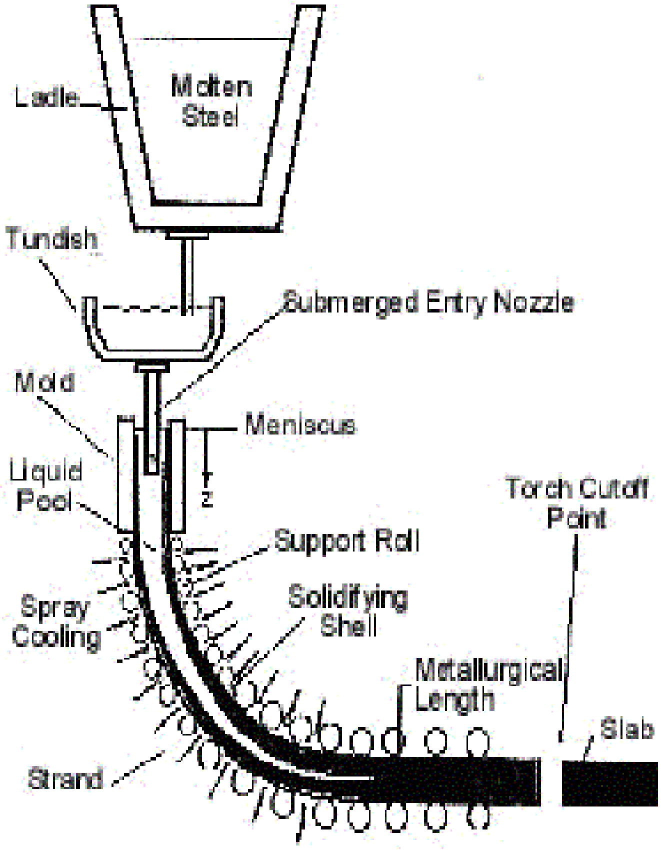


Fig. 1.2 – figure showing continuous casting machine

The continuous casting process starts from the tundish and continues till the solidification of material, thus CCP directly influence the various parameters such as production rate, steel quality, efficiency etc. and all the parts of the CCP plays very important role in this. (B.G THOMAS, 2003)

Continuous casting process is becoming very important compared to conventional ingot casting. In ingot casting, cast steel is taken to different manufacturing process which is very time consuming and also the ingots were very heavy so it take more time for solidification and also increases the production cost. To overcome from these problems continuous casting were involved and it is advantageous over ingot casting in terms of higher production rate, the material can cut in any desired length and it also increases the efficiency as the material is directly fed into the rolling operations which saves time.

The different steps of ingot casting are mold stripping, heating in soaking pits and primary rolling were replaced with single operation in continuous casting machine. In some cases, continuous casting machine also replaces reheating and rerolling steps.

Other advantage of using of CCP over ingot casting were –

1. Decrease in energy consumption
2. Production of scrap decreases which improves the yield
3. Increase in Labour productivity
4. Steel quality increases
5. Decrease in pollution
6. Capital cost decreases

1.2. Different Models developed for CCP

There are various studies conducted and different model was developed by so many researchers and scientists to study the various phenomena related to continuous casting process. The different phenomena related to continuous casting are -

1. Fluid flow phenomena
2. Inclusion behaviour
3. SEN choking and clogging
4. Quality of steels
5. Solidification problems
6. Cracks, porosity etc.

The different models provide various help to improve the different processes of continuous casting. The different models are the physical models, thermodynamic models, kinetics model and the mathematical models.

The physical models were used to understand the fluid flow phenomena in the continuous casting process through the various experiments using the water model. This model is helpful to understand the effects of new configurations before implementing them in the process. It is also helpful in the operator training and the better understanding of the process. (B.G THOMAS, 2003)

In the thermodynamic and kinetic model the different reactions occurring during the process and the rate at which the reaction occurs were calculated such heat transfer between the molten metal and the mold and solidification of molten steel in the caster during the process of continuous casting.

Mathematical model are mostly used to describe the various phenomena occurring inside the tundish, mold and SEN. Mathematical model include the computational model where the accurate analysis of the processes is done and is applied to full scale model for prediction. (B. G. Thomas, 2001). With the increasing power of computer hardware and software and the increase cost of empirical investigation and the, mathematical modeling is becoming an important tool to understand fluid flow phenomena (B. G. THOMAS et al., 2001)

1.3. Model classification

An exhaustive literature survey was done to and the different models were classified into two major groups which are as follows-

1. Thermodynamic and kinetic models
2. Water and CFD models

1. Thermodynamic and kinetic models-

Based on local force balance a particle capture model was developed using Computational Fluid Dynamics and applied to continuous casting process to predict the bubbles formation and slag inclusion entrapment in the nozzle and the mould with or without the effect of argon gas injection. To capture the movements of particles Lagrangian model was used and was validated by reproducing the results with two different systems. The results of fluid flow and particle transport model are applied together with the particle movement criterion are applied in slab caster to predict the different sized particle and the results shows that larger particles are easily removed as compared to smaller particles but defect is very high.(B. G. THOMAS et. al.,2013)

To study the turbulent, heat transfer and study state fluid flow in the continuous casting steel a 2D Finite element model was developed using the CFD code FIDAP. The main problem of this type simulation is the high Reynolds number which hinders convergence of solutions so different strategies based on altering certain things such as relaxation factors and mesh for obtaining good convergence. The Velocity(m/s) field and the flow patterns predicted by using this model is validated with the experimental data and water model made of plexiglass and the predicted profiles is closely matched with data so it shows good agreement with the data.(B. G. Thomas et. al.,1990)

The quality of steel in the continuous casting is greatly affected by the fluid flow which involves transient phenomenon and movement of inclusion particles in the mould region. A model was predicted using three different fluid flow phenomenons' and the accuracy was checked by comparing with the experimental data. The Velocity(m/s) simulated by the PIV method in the single phase model is applied to inclusion transportation in the mould region and the particle trajectory was calculated using LES model and is compared with the water model, LES model was good enough to match the data. Finally it was concluded that computational flow modeling has the potential to match with the real process and is better than the water model mainly when complex phenomenon such as multi phase flow and particle motion are involved. (B. G. Thomas et al., 2002)

Shear-layer instability is a crucial phenomenon in mold flux entrainment mechanisms in continuous casting molds also referred as Kelvin-Helmholtz instability which include argon bubble effects, surface level fluctuations, vortexing and suction down the SEN due to asymmetric fluid flow and excessive upward flow impingement on the meniscus. So for the study of above mentioned process a numerical model was developed to investigate the Kelvin-Helmholtz entrainment mechanism in steel continuous casters and it was validated with the simplified analytical solution of this phenomenon. (Lance C. Hibbeler et al., 2010)

For investigating fluid flow Velocity(m/s) in the liquid pool in mold region of the continuous caster of steel slab four different methods were used and compared. The results obtained from all the methods were compared and it shows a good quantitative agreement between all four methods for the surface velocities and overall time-averaged flow pattern for these conditions. All the four methods provide deep understanding in the study of transient and steady flow in the continuous slab-casting mold.(B. G. Thomas et al., 2001)

Many complex inter-related transient phenomena occur near the meniscus during the initial stages of solidification in continuous casting of steel slabs which causes surface defects such as periodic oscillation marks (OMs), and subsurface hooks. The study concluded that Oscillation marks form when molten steel overflows over the curved hook and solidifies by nucleation of under cooled liquid and sub-surface hooks is form by solidification and dendritic growth at the liquid meniscus during the negative strip time. Several plant observations, including the variability of hook and OM characteristics under different casting conditions are used to verify the model. (J. Sengupta, et, al, 2005)

A multi physics model of metal solidification was developed by combining thermo-mechanical behaviour of the solidifying shell, turbulent fluid flow in the liquid pool, and thermal distortion of the mold, the model is applied to commercial beam blank caster in continuous casting process. Standard k-ε turbulent flow model are used to solve the navier-stokes in the liquid pool of continuous casting process. Heat transfer model coupled with the stress model to consider the effect of gap formation and shell shrinkage on lowering the heat flux and the model is compared and verified with the analytical solutions obtained from the thermal stress in an unconstrained solidifying plate and benchmark problems of conduction with phase change (B. G. Thomas et al., 2011).

Heat transport in the liquid pool during continuous casting of steel slabs is investigated through a 3D unsteady state turbulent flow model using several different computational models. The model has been validated by comparing with PIV values in caster water models, and with Velocity(m/s) and temperature measurements in an operating steel caster. Study of thermal buoyancy and the solidifying steel shell walls effects are studied independently. It is very difficult to predict the heat transfer accurately then predicting accurate velocities. Finally, two different models are compared i.e. low Re-number K-ε and standard K-ε of Reynolds-averaged approaches, and the advantages and disadvantages of the different flow simulation methods are investigated.(Quan Yuan et al., 2005)

Transient flow in the mold is studied using a 3D finite-difference method. Studies involve flow pattern oscillations and rapid fluctuations in the molten steel/flux interval at the top of the mold. The predicted results matches with the experimental data and it was concluded that maximum fluctuation occurs near the narrow face without using argon while the use of argon increases the fluctuation towards the centre. It was also found that lower casting speed and deeper submergence decreases the fluctuations, these transient phenomena are very important as they directly influence the quality of steel and also cause the defects in the cast product. (X. huang et al., 1998)

LES and PIV measurements are used to study the transient flow in a continuous casting mold. Similar results and same transient flow features are seen from two methods that are very different from time-average flow pattern. Inlet swirl causes jet oscillations and complex vortex structures evolve and decay in both the upper and lower recirculation zones. The transient animations are used to visualize the flow structures. An inclusions particle trajectory was also investigated through the flowing liquid and is validated successfully with measurements. (B. G. Thomas, et, al, 2002)

The superheat transport and the flow of molten steel in the mold region in thin slab continuous caster were investigated in the transient state with LES model and the Plant experiments. The Velocity(m/s) predicted from the above model matches with the data obtained from the dye-injection experiments on full scale water models. The predicted temperature also matches the measurement done by thermocouple which is lowered into the molten steel during the process of continuous casting. Finally it was concluded that 2/3rd of the superheat was removed from the mold and the jets coming from the nozzle ports exhibit chaotic variations which produces temperature variations in the liquid pool (B. Zhao et al., 2005).

Most of the steel products are cast by continuous casting process but the large sized steel products are still manufactured by the process of ingot casting. Thus to replace the large sized ingot casting, a semi-continuous casting with maximum mold size was developed and simulated. The manufactured steel shows an improvement in quality of steel, so it was concluded that direct pouring of liquid metal to mold and extra slow casting speed increases the quality of the steel and simplified the operation. High quality steel was obtained from this caster which has more fine and uniform internal quality compared to ingot casting (K. Arakawa et. al., 1996).

Electromagnetic mold breaker is used to solve problems related to curve type continuous caster and high speed casting by controlling the flow of steel in the mold by using the static magnetic field. Surface Velocity(m/s) and meniscus profile are measured to optimize the EMBR operation and qualities of slab were inspected using various operating conditions mainly two different types of cores were used, different results were seen from the plant trial for each core. High position core which is simple linear type shows detrimental effect on the surface and internal quality of the slab, located near the SEN outlets where as low position core having magnetic insulator at the core located below the SEN decreases the non metallic inclusion and sub-surface defects in the slab mainly at high casting condition. (K H Moon, et al., 1996)

The center segregation in continuous casting is directly influenced by roll bending of all the mechanical factors and the test was conducted and it was found that center line segregation decreases with increasing the roll bending and it was found that use of divided rolls in the end of solidification is effective in decreasing roll bending and keeping the center line segregation at lower values (S. Ogibayasi 1991) .

Better surface quality and Crack free surface were obtained using the suitable casting parameters. An increase in casting Velocity(m/s) together with the increased power results in the fineness of the crystal grains and complete melting of the turnings (T. Tanak, 1992)

The effect of oxygen content on the chemical composition of tundish flux in the molten steel in tundish was investigated and from the experiments it was revealed that high basicity flux (CaO/SiO_2 approximately 11,O) is superior in decreasing oxygen content, compared with low basicity flux (CaO/SiO_2,=0.83). A mathematical model was also developed to predict the variation of oxygen concentration during casting and also the behaviour of oxygen. (N. Bessh, et al., 1992)

The behaviour of heat transfer in the mold region of continuous casting of steel was studied by performing experiments and overall thermal resistance with mold flux was also calculated on the parallel side of the plate. Quantitatively analysis of the thermal resistance and thermal conductivity of the mold flux was done and it was found that the interfacial thermal resistance disappears together with disappearance of air gaps when the temperature of the mold surface exceeds solidification temperature of the flux. Finally it was concluded that thermal conductivity of the mold flux is directly related to silicate ions and increases with the increase in size of silicate ion. (A. Yamauchkl, et al., 1992)

The non metallic inclusion in slab continuous caster and preventing the mold flux/slag from entering into the liquid steel can only be done if the flow pattern of molten steel is known, thus it plays an important role for the inclusion free casting. Different operating conditions are used to create different flow patterns. A numerical model was developed for turbulent fluid flow problems to simulate the flow in the molten steel in the mold, the model is good enough to predict the effect of nozzle design and operating condition on the flow patterns. Thus the best operating condition and the SEN design was obtain to cast the defect free steel. (Y. HOHO, et al., 1994)

To produce inclusion free steel is very tough and challenging process as inclusion causes serious defect problem which decreases the quality of the steel. For inclusion removal the vertical bending-type continuous casting machine is better than the bending-type continuous casting machine. The steel sheet defect and the flow pattern of the molten steel in the mold was investigated using the Reynolds k- e model and the most effective length for inclusion removal was calculated in the vertical casting and it was came out to be 2.5 to 3.0 mt. without considering the inclusion size and operating condition.(H. Tanak, et al., 1994)

Stress generation in casting process is a difficult to calculate using mathematical model, so the effort was made to numerically simulate the stress generation and the different operating condition, basic equation required to solve the model and other related phenomena were given. The model is coupled with transient heat transfer that includes temperature, stress, plastic-creep, solidification etc computational issues include numerical methods to handle these phenomena, mesh refinement and 2D stress state. Results obtained from FEM were given for validation. (B. G. Thomas, 1995).

Production of continuously cast steel was subjected to small lot sizes and also to complex user requirements. To meet such requirements, a new technology was in which a hot tundish is used repeatedly. As a result this, energy, refractory and labour costs have been reduced, and it also increases quality and productivity of steel. The improvements in quality were achieved during the start and end of casting operations and also during the ladle exchange in unstable casting conditions. (K. Tanikawas et al, 1996)

To study the changes in the composition of the mold flux and the reaction between the mold flux and the molten steel a mathematical model was developed. Heat transfer in the molten flux and steel and equilibrium reaction at the interface was considered. The activities of general mold flux components like CaO .SiO2, Al2O3 was calculated by statistical thermodynamic model of slag also called cell model. The data obtained from the mathematical model was compared with the data obtained from the experimental process and from the compared data it was concluded that mathematical model is capable of predicting the reaction between the mold flux and the molten steel and it also helpful in designing the optimum flux composition in the mold in the continuous casting process. (A. Kiyose. et al., 1996)

A mathematical model based on SOLA method was developed to study the flow behaviour of molten steel in the billet continuous casting mold. The effect of SEN design on flow pattern was analyzed by using this model and the effect of different operating condition on flow pattern was also investigated and it was seen that the efficiency of non-metallic inclusion removal was increased. (Yeong-HoHo et al., 1996)

The main features of steel casting and solidification process were studied by using a mathematical model. Important information from the model shows the interaction between the fluid dynamics i.e. flow pattern inside the mold and at the meniscus and the thermal aspects i.e. temperature variation at the slab surface and at the solidified shell was achieved. In the case of fluid dynamics different operating conditions were checked particularly shape and size of SEN and in the thermal case it gives information on the shell growth rate and the dissipation of superheat. The path of non-metallic inclusion was predicted from the thermo-fluid dynamic model and is compared with the data obtained from the literature and experiments. (M. De santis et al., 1996)

A new process for high temperature alloys and steels was developed called continuous rheocasting by Inland steel incorporating which uses dual chamber casting machine and separately utilizes the electromagnetic stirrers around the each chamber. The solidification mechanism and the formation of cast surface structure on as rheocast bars were determined and validated by comparing with the predicted surface structure to actual surface structure. To eliminate sticker breakouts and to obtain good surface quality, the new surface withdrawal pattern was developed using this model. (K E. Blazek et al., 1996)

The thermo-mechanical behaviours of the mold and strand were analyzed by using a 2D FEM model coupled with thermo-elastic-plastic. The calculated temperature distribution and the geometry around the solidifying shell and mold region were compared with experimental data and compared results show good agreement as the calculated geometry around corner region matches with the experimental data. The “apparent wear parameter” a dimensionless number used to analyzed the mold wear which is directly proportional to the interfacial pressure between the mold and the strand and inversely proportional to the yield stress of the mold at service temperature. This dimensionless number is used to analyze the effect of narrow face taper on mold wear and it was seen that the possibility of mold wear increases with increasing narrow face taper, due to increasing interfacial pressure. The behaviour of mold calculated from the model was compared with the used mold in industrial operation and it was in good agreement with industrial operations. (Y. Mok Won, et al., 1998)

To study the transport phenomena in the continuous casting process which include heat transfer, fluid flow and solidification, 3D coupled model was developed. In a solid-liquid multicomponent phase system, the continuous casting process is considered as a solidification process. To model the occlusion .i.e. blockage of fluid flow by columnar dendrites in the mushy zone, porous media theory was used. The relation between shape of the solid shell and the flow pattern is also shown. The double diffusive convection caused by concentration and thermal gradients was considered with that the change in the liquidious temperature with liquid concentration was also considered. The formation mechanism of macro segregation was also investigated. For validation the calculated solid shell thickness and temperature distribution in liquid core are compared with the measured quantities. (Hongliang Yang et al., 1997)

Surface quality of the cast slab of medium carbon steel is directly depends on the heat transfer in the continuous casting mold, so it plays an important role in the quality of steel.
Many researchers have studied the mechanism of reducing heat transfer between the mold and the solidified shell and they concluded that heat transfer is decreased by the interfacial thermal resistance between the mold and the surface of the solidified mold flux. In this experiment the surface roughness of solidified mold flux was measured by confocal scanning laser microscope combined with an infrared image furnace of low and medium carbon steel. From the experiment it was found that surface roughness depends on the cooling rate as increase in cooling rate gives smooth surface roughness and it was also found that surface roughness of the mold flux became rough for medium carbon steel in comparison to low carbon steel. The experimental data were verified by comparing with the calculated data and it shows fair agreement with the calculated data. (K. Tsutsumi et al., 1999)

For the simulation of steel continuous casting a 2D finite element method using global non-steady state approach was carried out and deformation, temperature and stresses were calculated along the continuous casting machine. Both the axis symmetry and plane deformation were developed and earlier one was applied to cylindrical billets whereas the former one is used for the simulation of slabs in the continuous casting by considering the possible curvature of machine. The method was validated by comparing with the results from the literature and was applied to slab continuous caster for which successive compressive stress were revealed in secondary cooling zone region.(M. Bellet et al., 2004)

2. Water and the CFD model

The trajectory of the fluid, bubbles and solid particles in liquid steel were investigated in the continuous casting tundish, mould and strand and steel ingot casting processes. Multiphase flow is also simulated using VOF, Eulerian- Eulerian and Lagrangian-method. These models are used in good numbers to predict inclusion trajectories, inclusion removal fraction, free surface waves and other relevant phenomena (L. Zhang & B. G. Thomas, 2005).

Misalignment in metal delivery system can detroits the quality of final product and causes inclusion entrapment, abnormal surface turbulence, slag entrapment, insufficient superheat transport to meniscus and other problem. This paper describes the effect of stopper rod misalignment on nozzle and mold flow velocities by using a water model and a CFD model of continuous casting (R. Chaudhary, et al., 2011)

CFD models were applied in turbulent flows, multiphase flows to develop new process for steel making i.e. new scrap based which revolunitize the way of making the steel. Continuous casting of steel is uses the energy in an efficient way, it also lowers the production cost and increases the quality of steel. This paper describes how CFD is helpful in designing metallurgical process (L. Zhang et al., 2005)

Fluid flow in mold region affects the quality of steel because of the entrapment and transport of inclusion particles. A quantitative model was developed to study the fluid flow and inclusion phenomena in the continuous casting of steel and was applied to improve understanding and inclusion removal. The results of five interrelated sub projects shows that only a small fraction of the total number of mainly-small inclusions entering the caster appear to be removed, so there is motive to remove them during upstream processing.(B.G. Thomas, et. al, 2003)

A water and computational model of the transient fluid flow were studied for study and transient case. Flow field measurements were calculated from the water model using PIV method in steady state condition and then computational model using CFD software, Fluent with k-e turbulence model is simulated and the results from the CFD model is compared with the water model and it shows good agreement with the water model, so the result is validated and the computational model is accepted. (A. Braun, et al., 2010)

Argon bubble behaviour was analyzed in the continuous casting process by using different models such as water model, mathematical models and the plant data and it was concluded that argon bubble is very important in SEN clogging as it protects the wall of SEN from alumina oxides by collecting inclusion and greatly increase their removal. It also shows that the size of argon bubble increases with decreasing steel flow rate and increasing gas flow rate. (B. G. Thomas, et. al., 1997)

A CFD model was developed to study the composition distribution during grade change in continuous casting steel. The model consists of three sub models which accounts for mixing in the tundish, mixing in the liquid core of the strand, and solidification. The model has been simulated using both concentration histories measured on tundish water models and calculations from a 3-D model. The model is capable of predicting mixing phenomena for casting histories and arbitrary tundish filling. The effects of different grade change procedures on the amount of intermixed steel casting, and insertion of grade separators are also compared using this model. Finally it was concluded that Mixing in the strand is very important. (X. Huang, et, al.1996)

In continuous casting the quality of steel is directly related to fluid flow phenomena and to understand and predict the fluid flow in continuous casting mold region mathematical model is the best. the fluid flow phenomena includes multi-phase flow phenomena, the effect of electromagnetic forces, heat transfer, turbulent flow in the nozzle and mold, the transport of bubbles and inclusion particles, interfacial phenomena and interactions between the steel surface and the slag layers, the transport of solute elements and segregation (B. G. Thomas et al., 2001) .

The steel quality in the continuous casting is directly influenced by the fluid flow phenomena in the mold especially in the meniscus region. A CFD model was developed to study the different types of defects cause by fluid flow. The amount of gas injection in tundish is calculated from the model to avoid aspiration effect. Effect of superheat is also calculated and it was concluded that decrease in superheat resulted sub-surface hooks defects. To simulate the transport and entrapment of particles Transient, turbulent flow models were and it provides a great help in modeling and avoid such defects. (B. G. Thomas, 2005)

To study the flow pattern in the mold from Nozzle and the effect of nozzle shape i.e. well shaped bottom and mountain shape bottom nozzle are consider in the continuous casting process, a CFD model was developed and the flow pattern was investigated under steady state and transient condition. The results obtained from the CFD model using k-e turbulence model are compared with the experimental data done on one-third scale water model and PIV method and it was concluded from the results that nozzles with a mountain-shaped bottom are more susceptible to problems from asymmetric flow, low-frequency surface-flow variations, and excessive surface velocities. Thus the study shows that nozzle shape plays an important role in the flow pattern in the continuous casting. (R. Chaudhary et al., 2008)

The flow phenomena occurring inside the tundish can be seen from the water model of the tundish and most of the water model was investigated using isothermal condition generally at room temperature but fluid flow inside tundish is not isothermal. Thus a water model was proposed to simulate the flow of molten steel inside the tundish by using navier stokes equation and the different cases are simulated using the water model and the mathematical model and results was verified by comparing the data obtained from the two models and it shows good agreement as the residence time calculated from the water model almost matches with the mathematical model. (C. Damle et al., 1996).

Various efforts were made to fully exploit and enhance the metallurgical performance of tundish in the continuous casting process over last two decade. To achieve these goals various physical and mathematical modelling of water and industrial tundishes were made and studied and were classified into three categories i.e. (1) mathematical modelling, (2) physical modelling and (3) combined physical and mathematical modelling. Various research were made considering various aspects of modelling criteria of tundish metallurgy such as residence time distribution (RTD), turbulent fluid flow, heat loss and temperature drop, inclusion transport, grade transition etc. was reported. Comprehensive and sufficient reliable model are also available and these model are good enough to predict full scale model and also useful in better designing and process calculation but still there are some uncertainties which remains there for further research (D. Mazumdar et al., 1999).

To study the heat transfer and fluid flow in a thin liquid slag layer or flux a coupled numerical simulations were carried out using CFD software, FLUENT and the Navier–Stokes steady state equations were solved. The combined effects of bottom shear Velocity(m/s), natural convection and viscosities strongly dependent on temperature were investigated. From the model it was seen that the variation of Nu with Ra for fluxes with viscosities dependent strongly on temperature was analogous to correlations for fluids with viscosity remains constant, but the critical Rayleigh number for the onset of natural convection is larger. Natural convection was suppressed for thin layers of realistic fluxes, and nusselt number increases linearly with the increase of bottom shear Velocity(m/s). The increase seen was greater for the decreasing average viscosity. (B. Zhao, et al., 2004).

Inclusion removal by bubbles during the continuous casting process of steel is becoming very important factor for the defect free casting. Computational models were developed to study the inclusion removal process. Firstly the inclusion probability on bubble surface was simulated using the fluid flow phenomena considering the turbulent inclusion trajectory and sliding time of each single inclusion along the bubble surface as a function of bubble size and particle. After that the path length and trajectories of bubble particles in the continuous casting mold was calculated using the turbulent fluid flow. Due to the transport of bubble in the mold, the change in inclusion distribution was simulated based on probability of inclusion on each bubble and the path length of bubbles computed from above model. Finally the result shows the importance of different processes of inclusion removal. (L. Zhang et al., 2004)

Various efforts were made to study the mold and SEN performance in the continuous caster of slab. Various numerical and physical modelling were developed to study the fluid behaviour inside the mold. An extensive literature survey was done and model was categorized into two groups that is physical modelling and the numerical modelling and the importance of water and CFD modelling to the fluid flow problems was illustrated. (P. Mishra et al., 2012)

Water model experiment was carried out to study the metallurgical effect of a round tundish which was used to cast heavy steel ingots in machine works. Oval tundish with improved flow control devices was used instead of the round tundish. The residence time calculated for the round tundish is short compared to the oval tundish, its inclusion removal efficiency is also very low, and it has an unreasonable flow field and more dead zones, where as in the improved oval tundish with optimized dam and weir has a better effect, its minimum residence time is prolonged by 38.1 s, whereas the average residence time is prolonged by 233.4 s, dead volume fraction decreases up to 11% and the ratio of volume fraction of plug to dead volume fraction increases from 0.54 to 1.27. The efficiency of inclusion removal was also increased by 17.5%. (G.Wen et al., 2011)

A physical model was developed to optimize the flow control devices in a tundish of a single-slab continuous casting process. The residence time of the tundish was increased by 1.4 times with the use of optimal tundish configuration, the fraction of dead volume was decreased by 72% and the peak concentration time increases up to 97%. A CFD software FLUENT was used to develop a mathematical model for the flow of molten steel in the tundish of continuous casting process. Different curves of molten steel before and after the optimization were obtained such as concentration field, Velocity(m/s) field, and the residence time distribution (RTD). From the experiment it was seen that with flow control devices characteristics in the tundish was improved and from the results of industrial application it was seen that the ratio of non-metallic inclusion area was decreased by 32% in the casting slabs with the use of optimal tundish configuration (N. Ding et al., 2010)

CFD is a very good tool for better understanding of the fundamental processes of engineering application and various studies were conducted to prove the importance of CFD. CFD can help in the various field such as in the field of continuous casting of steel which includes turbulent flow, impact of soft reduction and the motion and entrapment of non-metallic inclusions, in the field where multiple flow phenomena and multi scale aspects during the large ingot casting, including the flow-induced in the columnar-to-equiaxed transition and the 3D formation of channel segregation and in the multiphase magneto-hydrodynamics during electro-slag remelting and also in the melt flow and solidification of thin but large centrifugal castings (A. Ludwig et al., 2013)

An open source CFD software called Open FOAM is used to study the flow of molten metal in a T-type two-strand bloom caster tundish under the influence of flow control devices study was done on three different tundish i.e. a bare tundish, a tundish with two pairs of baffles, and a tundish equipped with a turbulence inhibitor and a pair of baffles. The results from the study shows that the turbulence inhibitor and baffles arrangement showed an improvement in the fluid flow characteristics, yielding to lower values of dead volume and the higher values of plug flow. With the turbulence inhibitor, the metal Velocity(m/s) which flows directly towards the tundish floor is smaller and the turbulence kinetic energy of the melt top surface is lower than the other two arrangements. (Z. He et al., 2013)

1.4 Technology Gap and Objectives

Detail study of fluid flow path considering slag and steel different phase of multiphase CFD modeling is not reported in literature for tundish and mold combined assembly of continuous casting machine. In the intention of working for reducing the gap, the objectives of thesis work is,

1. Fluid flow based floatation behavior study of inclusion inside tundish and mold of continuous casting process of steel.
2. Investigate and provide concrete guidance regarding the effect of flow controller on the inclusion floatation behavior by taking care of residence time concept.
3. Introduction of multiphase CFD modeling for detailing the interdependency of geometry of tundish-mold assembly and flow characteristics of steel and slag.

Chapter-2

Methodology

In this thesis, a 2D tundish with and without Dam and Weir and with and without mould is simulated in the continuous casting process. The simulation was carried out by using computational fluid dynamics modeling. For CFD analysis, ANSYS 15 software is used. FLUENT is the ANSYS solver to solve the fluid related problems. The solver is based on Finite Volume method. Before CFD simulation, domain is discretized into a finite set of control volumes.

There are some steps to solve ventilation simulation as following –

1. Problem identification

2. Pre-Processing

3. Solution

4. Post-Processing

Figure represents different steps of solving problem using CFD analysis

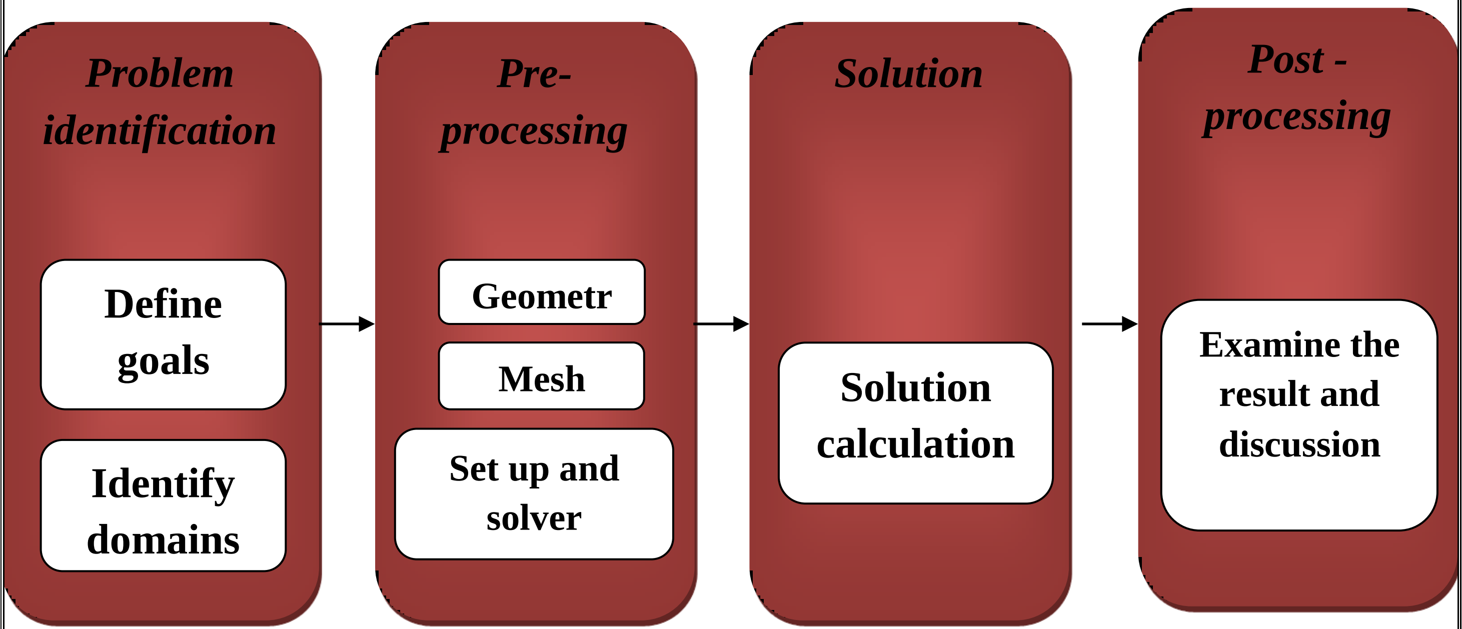


Fig. 2.1 - Steps in CFD solver

2.2Problem identification-

Define goals - In this section, the goals according to the problem are identified. The ultimate objective is to reduce the turbulent intensity in the continuous casting process.

Identify domain – In this section, we identify the domain of our problem. In continuous casting, we identify different domain like inlet, outlet, wall or free surface.

2.3 Pre processing-

Pre processing is the initial stage of modeling. The geometry of the tundish with and without mold of the continuous casting process is developed using design modular of the ANSYS 15 software. Then the model is meshed or discretized into smaller domain by mesh module. After completing the meshing, the model is simulated using the FLUENT solver in ANSYS 15. The different parameters used for the simulation are set according to fluid model, material properties, boundary conditions, solving techniques, turbulence model, criterion etc. the objective is maximized i.e. the turbulent intensity decreases at the end.

A. In pre processing there are three steps which are –

a. Geometry drawing
b. Meshing
c. Solver and set up settings

2.3.1 Geometry Drawing –

Geometry drawing is done in the design modular. A 2D model of the tundish of continuous casting process with and without the mold was drawn. The sketch and complete geometry with dimensions are shown in the figure3.2 and 3.3 given below and the complete geometry with the different named section sections are shown in the figure 3.3 below. The geometry is made to reflect the actual tundish with and without mold of the CCP.

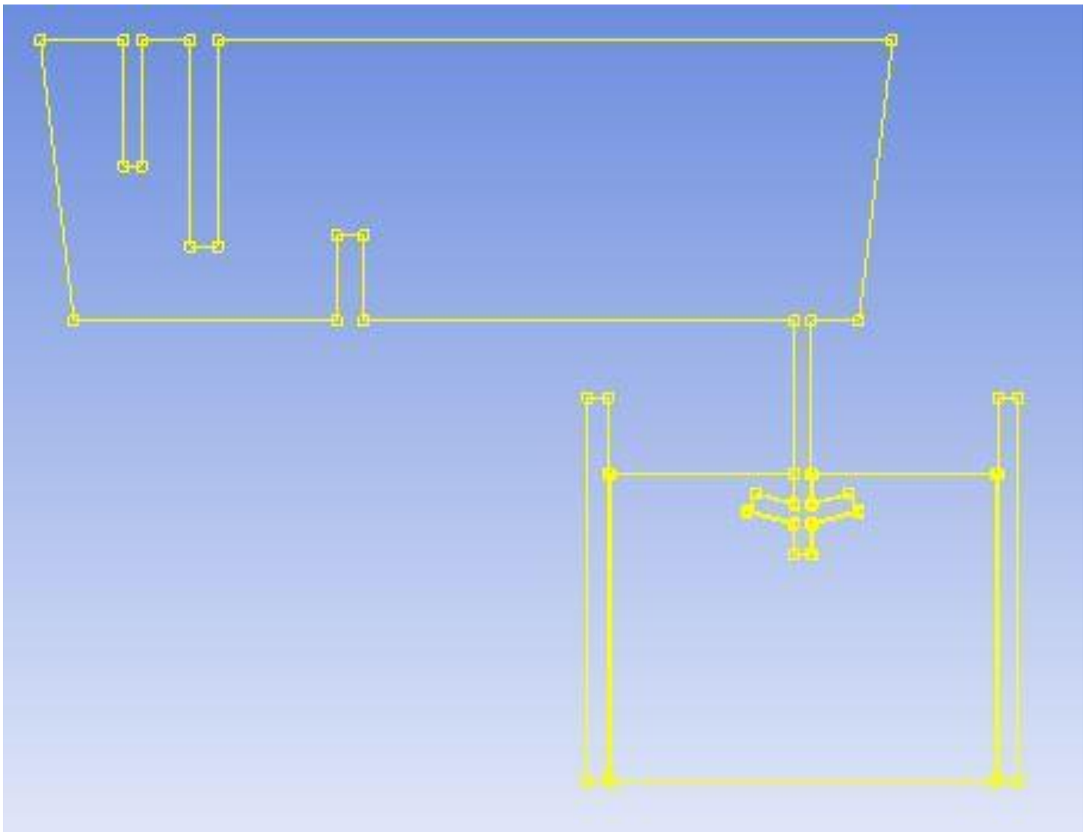


Fig. 2.2 – A 2D sketch of the model of CCP

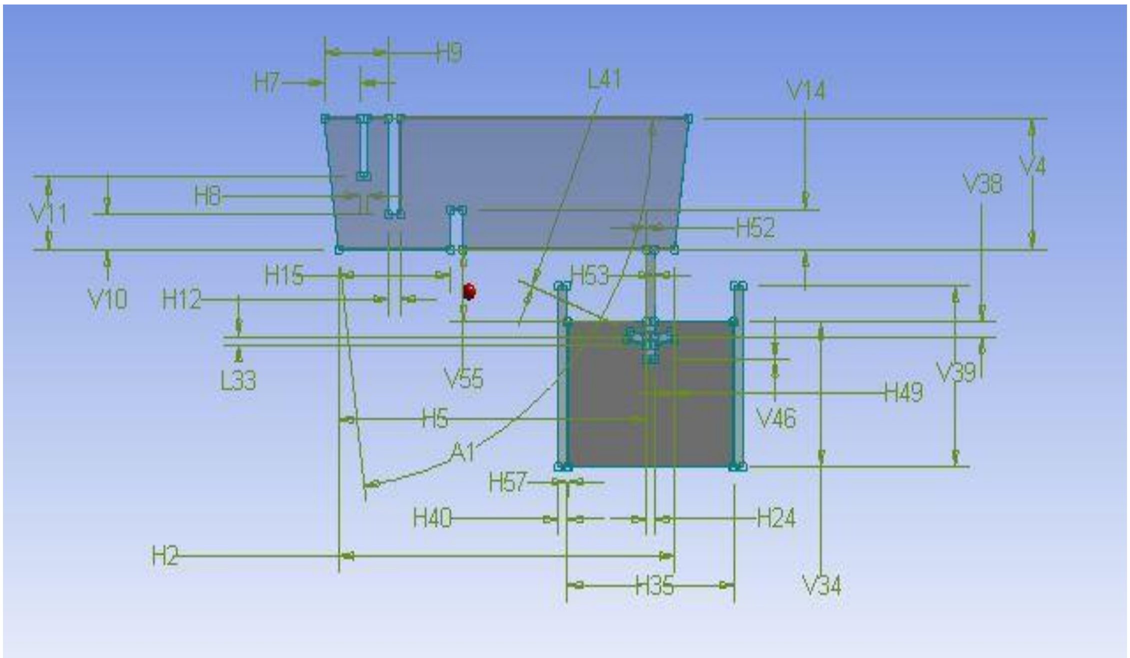


Fig.2.3 – complete sketch of 2D geometry with dimension

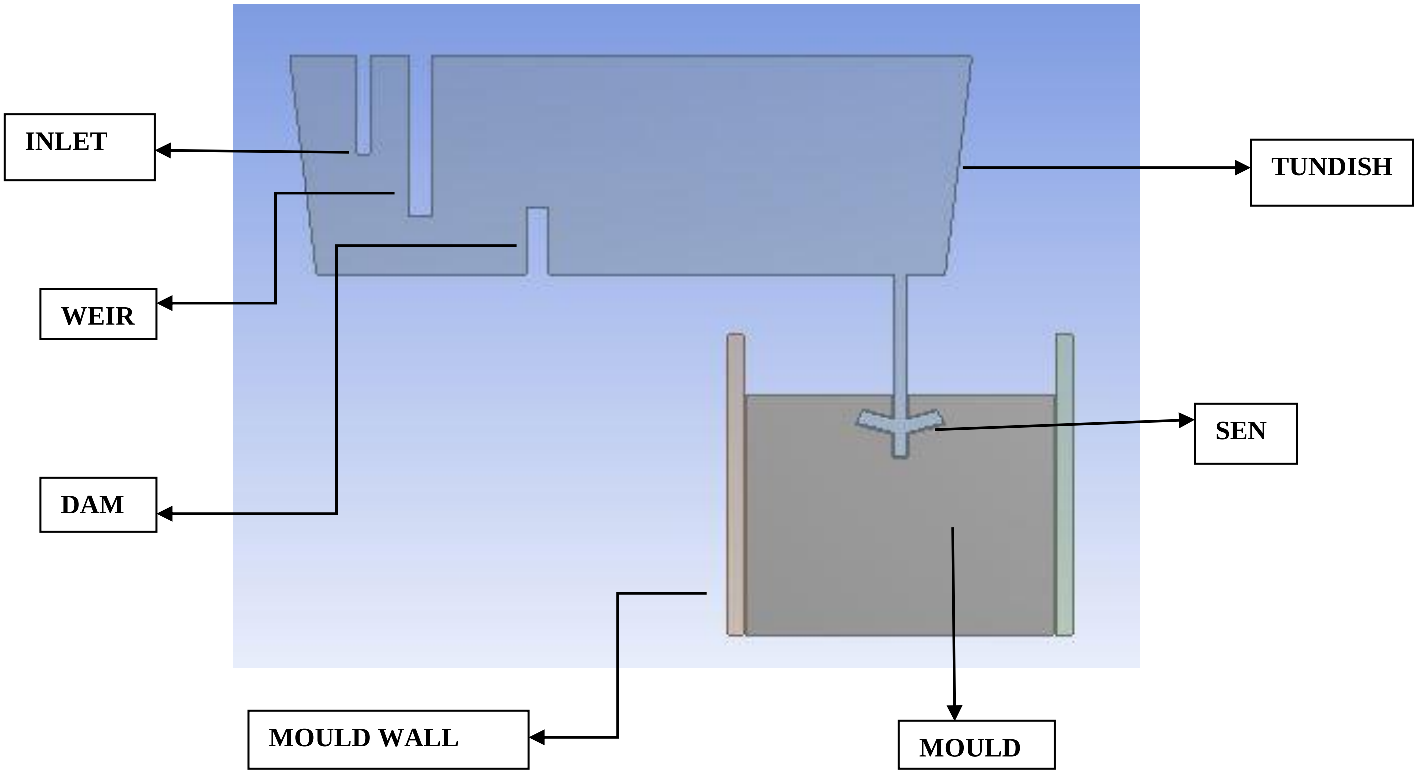


Fig.2.4 – complete sketch of 2D geometry with named section

The dimensions of the tundish,SEN, mold, dam and weir are shown in figure 3.5 below

Table 3.1 Dimension of geometry parts

Tundish height	1.09mt
Tundish width	3.14mt
Angle of inclination	83
Distance of Dam from the bottom	0.29mt
Weir height	0.33mt
Dam position from the inclination	0.6mt.
Weir position from the bottom of the inclination	1.05mt
Outlet from the bottom of inclination	2.88mt
Inlet from the inclination	0.335mt
Height of mold wall	1.5mt
Thickness	0.08mt
Distance between the wall	1.56mt
Meniscus	0.12mt
Angle and Width of SEN port	15° and 0.07mt.

2.3.2 GRID Formation(MESHING) –

- CFD uses numerical technique to solve equations, so it requires a Discretization of variables, for this we have to create meshing or grid.

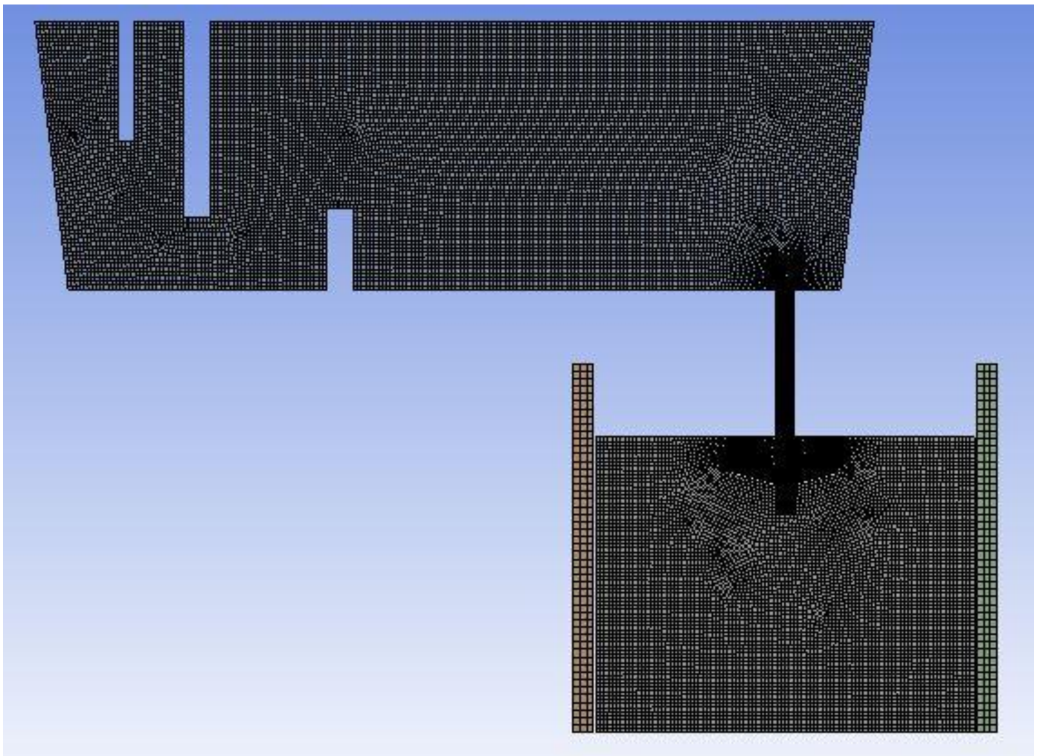


Fig.2.5 – Meshing of the entire model

- The quality of mesh can be check by different ways like skewness, aspect ratio, element quality etc.
- Here we have shown quality by element quality and skewness.

Meshing quality by element method

- The maximum no. of element of the mesh should be close to 1 is considered as good mesh.
- In our meshing the minimum no. of elements is 0.13 and the maximum is 0.99, the maximum elements are closed to 1.
- The statistics of mesh by element quality is shown below table3.2-

Table 3.2 mesh statistics by element quality

Nodes	23612
Elements	22716
Mesh Metric	Element Quality
Min	0.137085773849786
Max	0.999602136406598
Average	0.9483336918799
Standard Deviation	6.93923173606425E-02

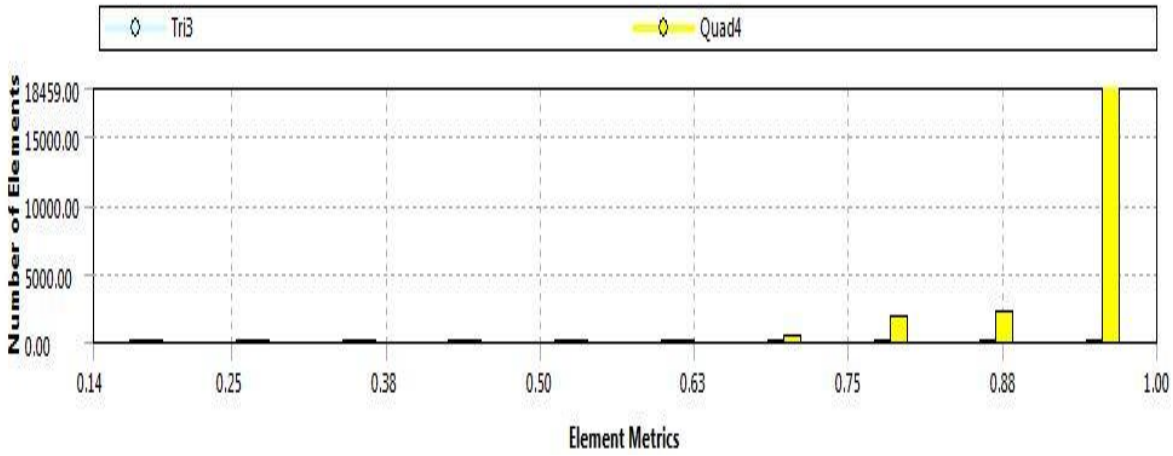


Fig.2.6 - Meshing graph by element quality

- In the graph shown above in figure. 3.7, the maximum numbers of elements are close to 1.

<u>**Meshing quality by skewness**</u>

- The skewness of the elements should be close to 0 and it can be acceptable upto 0.8
- The statistics with skewness is shown below in table 3.3-

Table 3.3 mesh statistics by skewness

Nodes	23612
Elements	22716
Mesh Metric	Skewness
Min	1.3057293693791E-10
Max	0.701010530987791
Average	5.64584916654852E-02
Standard Deviation	7.40883373545059E-02

➢ Skewness by graph is shown below in figure 3.7

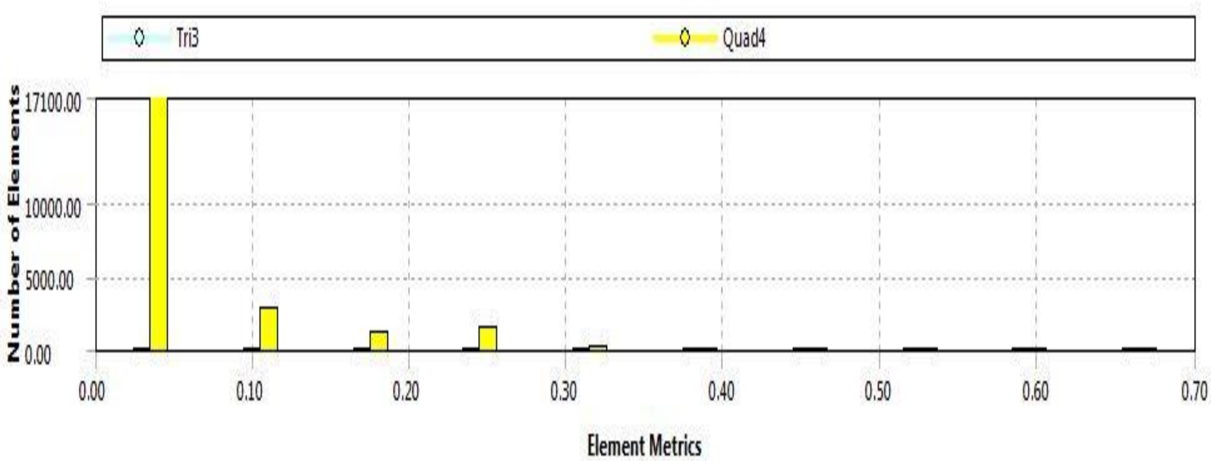


Fig.2.7 - Meshing graph by skewness

➢ The yellow colour shows quadrilateral mesh where as light green shows triangular mesh

➢ Both the meshes are shown below-

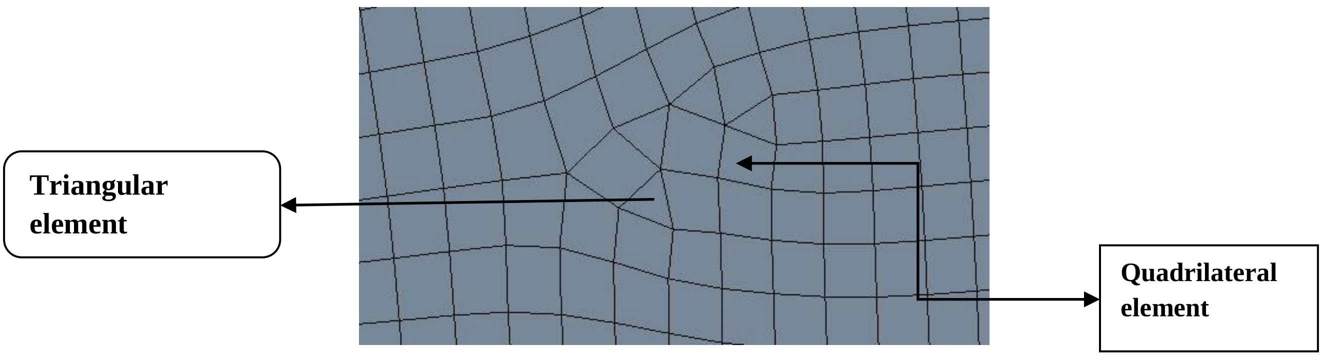


Fig.2.8 – showing triangular and quadrilateral mesh

.

2.4 Solver setup and Solution-

After the meshing is completed the model is imported to FLUENT software and firstly the mesh and mesh quality were checked and if the meshing is not good then error will be shown and simulation will not be access further.

2.4.1 The governing equation-

The governing equation of computational fluid dynamics (CFD) is known as Navier-Stokes equations. The Navier-Stokes equations consist of conservation of mass, momentum, energy, species etc equations. The governing equations are following-

Conservation equation of mass

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho.V) = 0$$

Conservation equation of momentum

$$\frac{\partial \rho V}{\partial t} + \nabla.(\rho.VV) = -\nabla p + \nabla.\bar{\bar{\tau}} + \rho g$$

Turbulent model equation-

The *k*-*ε* turbulent model is used for this experiment. Where *k* is the turbulent kinetic energy and *ε* is turbulent dissipation energy, the governing equation for this are-

The turbulent kinetic energy *k*, is give by-

$$\frac{\partial}{\partial t}(\rho.k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\varepsilon - Y_M + S_k$$

Turbulent dissipation rate *ε* is given by

$$\frac{\partial}{\partial t}(\rho.\varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\epsilon}{k}(P_k + C_{3\varepsilon}P_b) - C_{2\varepsilon\rho}\frac{\epsilon^2}{k} + S_E$$

Production of K-

P_k Represent the generation or production of turbulent kinetic energy due to mean Velocity(m/s) gradient and is calculated by-

$$P_k = -\rho u_i u_j C_\mu \frac{k^2}{\varepsilon}$$

$$P_k = \mu_t S^2$$

$$P_k = \sqrt{(2}S_{ij}S_{ij})$$

Modelling turbulent viscosity-

μ_t is the turbulent viscosity and is calculated as

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

The values of constant are

$$C_{1\varepsilon} = 1.44$$
$$C_{2\varepsilon} = 1.92$$
$$C_\mu = 0.009$$
$$\sigma_k = 1.0$$
$$\sigma_\varepsilon = 1.3$$

For the 2 phase flow VOF model is used and the governing equation for that is –
The tracking of the interfaces between the phases is accomplished by the solution of a continuity equation for the volume fraction of one or more of the phases.

For the q^{th} phase, the governing equation is

$$\frac{1}{\rho_q}[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla.(\alpha_q \rho_q \vec{v}_q) = S_{\alpha q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})]$$

Where

$\dot{m}_{pq}$ Is the mass transfer from phase P to Q,

$\dot{m}_{qp}$ is the mass transfer from phase Q to P and

$S_{\alpha q}$ Is the source term

The equation will only be solved for more than one phase if only single phase is present then governing equation is

$$\sum_{q=1}^{n} \alpha_q = 1$$

2.4.2 **Setup data-**

For simulation purpose, some date like fluid material, solver, turbulent model and boundary Conditions, solution method, convergence criterion etc are assumed to be known. Table 3.3 Shows the input data according to problem and what we want in results.

Table 3.4 – Operating Parameter

Solver	Pressure-based
Time	Steady and transient
Turbulent model	Standard turbulent k-ε model
Material	Liquid steel
Operating pressure	101325 pa
Number of iteration-	
Steady state-	Till the convergence occur
Transient state	60 seconds

2.5 Solution -

After applying the boundary condition the different cases are run in both the steady and transient condition.

The different cases run are-

A. Single phase –

In single phase different cases run are -

1. Steady state tundish
2. Transient state tundish
3. Transient state tundish with dam and weir
4. Transient state tundish with curve dam and weir
5. Steady state tundish with mould
6. Transient state tundish with mould
7. Transient state tundish with mould and dam and weir

B. Two phase –

In multiphase only two cases are run which are as given below-

1. Two phase with tundish with dam and weir
2. Two phase with mould with dam and weir

C. DPM modal-

In DPM model a massless particle is injected through the surface of the inlet and particle trajectory is seen and also the residence time is calculated for some cases

A. Single phase-

- In single phase we have taken following boundary conditions-

Table 3.5 – Material properties

Density	6800 $kg/mt.^3$
viscosity	0.0059 $kg/(mt.sec)$
Velocity(m/s)	1.69 $mt./sec$
For 2 phase	
1st phase	Slag
2nd phase	Liquid steel
Slag density	2500 $kg/mt.^3$
Surface tension	0.4 N/ $mt.$

- Different profiles obtained in different cases are which were studied and discussed in the result and discussion

Chapter - 3

Results

And

Discussions

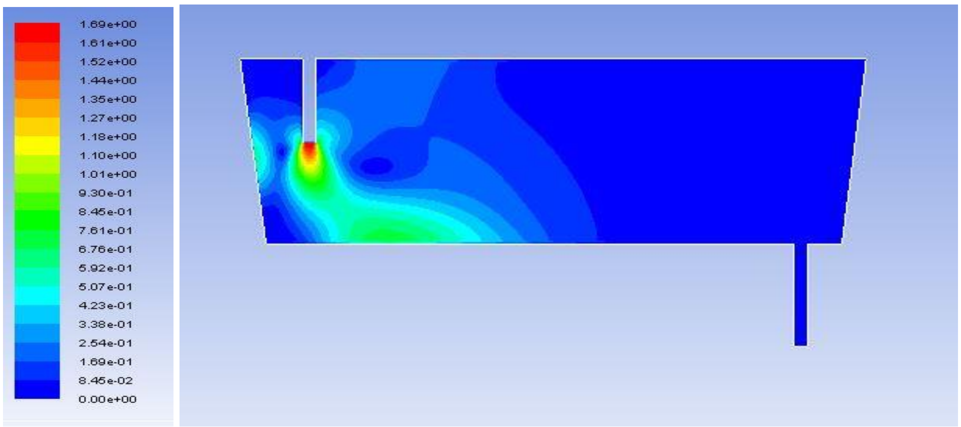
Firstly only tundish without mold is run with and without the dam and weir and the different profiles are obtained which are given below—

3.1.1 Steady state tundish

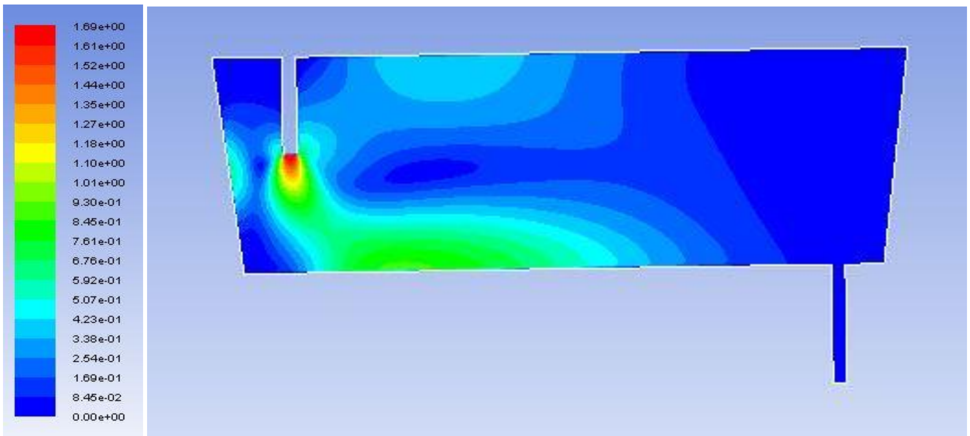
Firstly the model is simulated in steady state till the convergence of the residuals.

- The solution converged at 3000 iterations.
- Velocity(m/s) and turbulent profiles are shown
- Profiles at 1500 iterations and 3000 iterations are shown and compared

Velocity(m/s) profile-



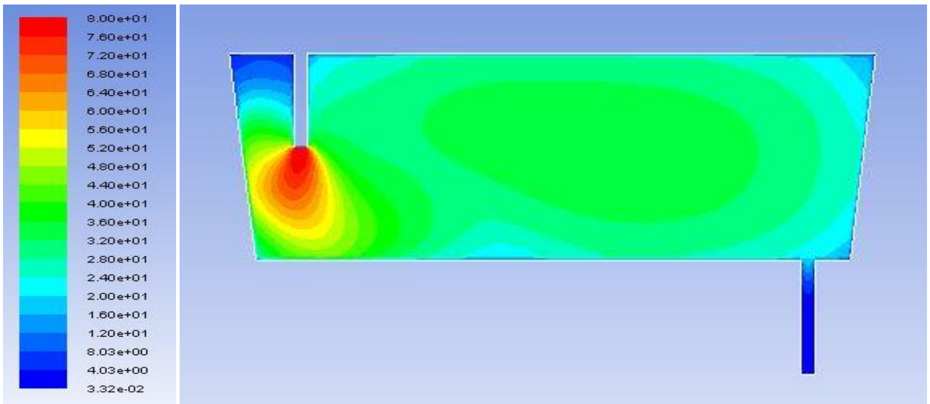
(a)



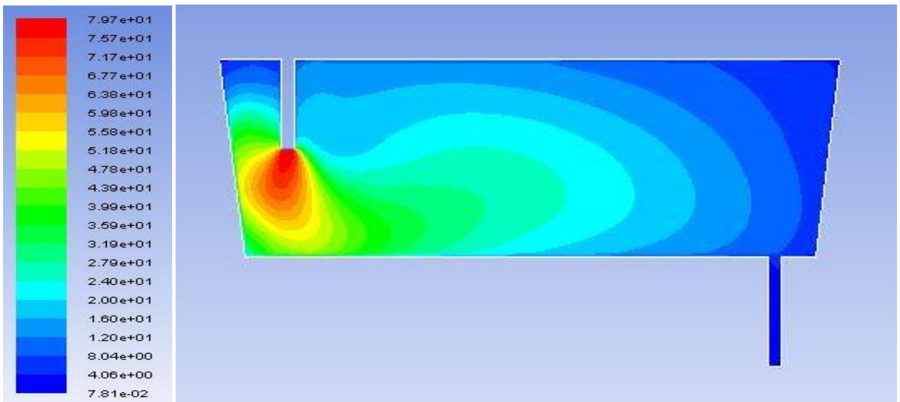
(b)

Fig.3.1.1. – showing Velocity(m/s) profile in steady state (a) at 1500 and (b) at 3000 iterations

Turbulent intensity profile-



(a)



(b)

Fig.3.1.2. – turbulent intensity profiles (a) at 1500 iterations and (b) at 3000 iterations

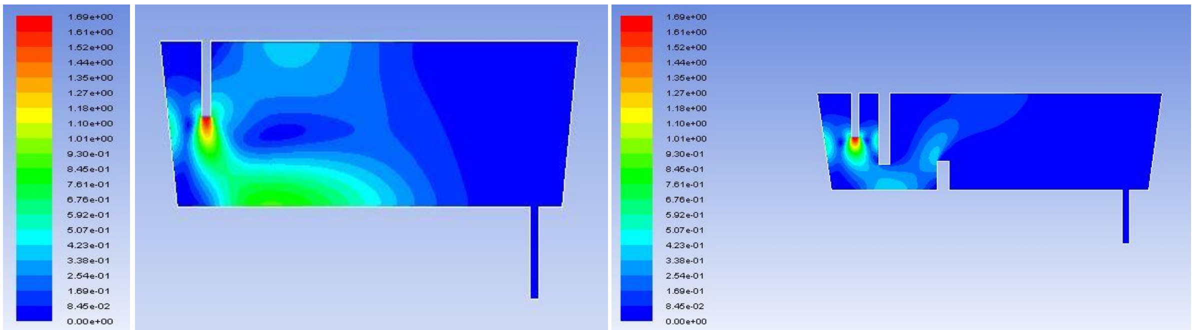
The Velocity(m/s) profile shows the flow motion of the liquid material with the slag and turbulence intensity profiles shows the dissipation of turbulence in a model. Steady state cases are run to check the stability of the solution and also the convergence of the solution

3.1.2 Transient state tundish-

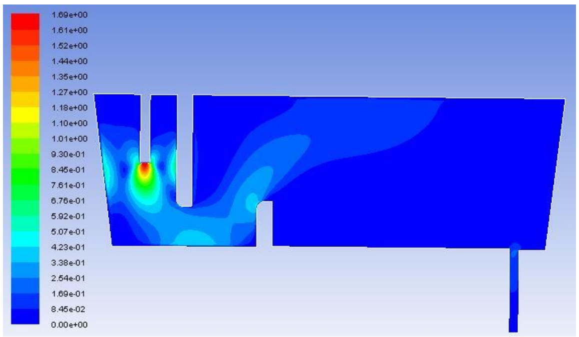
- All the transient state cases have been run for 60 seconds with time step size is 0.01
- Velocity(m/s) and the turbulent profiles have been shown at 30 sec and at 60 sec

Velocity(m/s) profile-

Velocity(m/s) profiles are shown below for 30 sec-



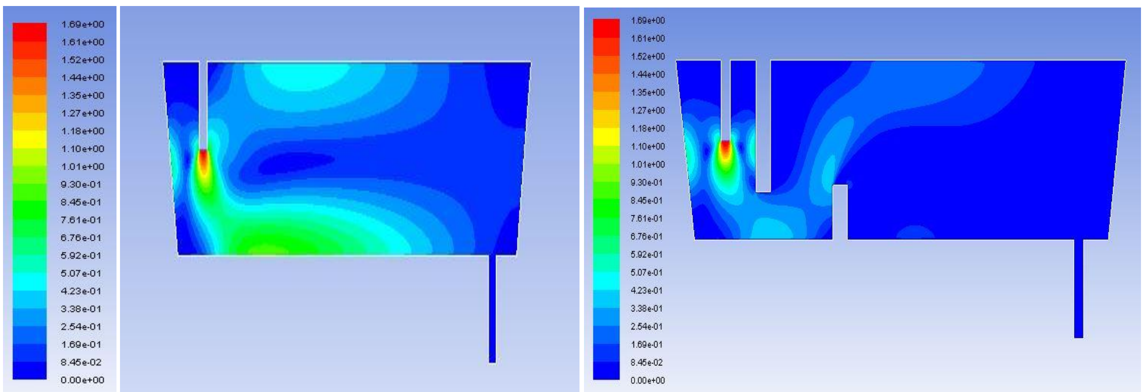
(a) (b)



(c)

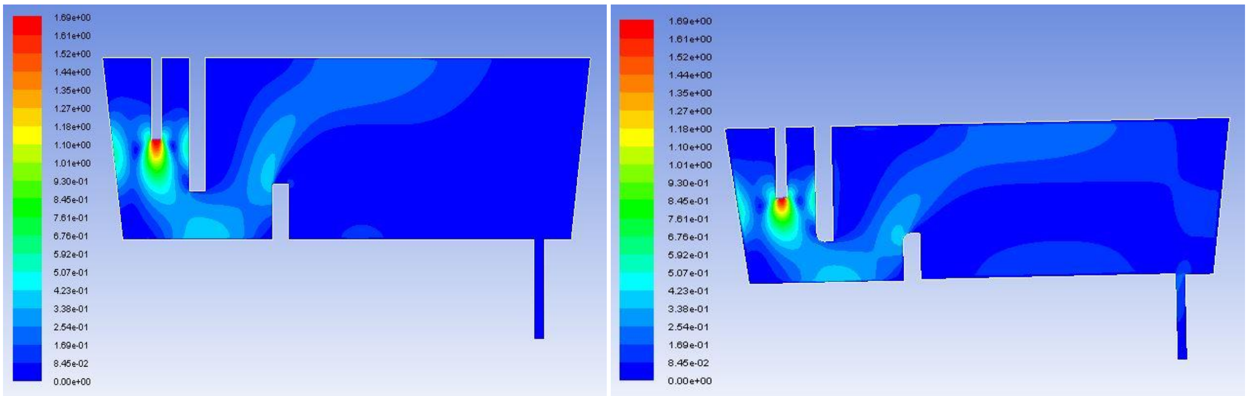
Fig.3.1.3 –Velocity(m/s) profile at 30 sec (a) without dam and weir (b) with dam and weir (c) with curve dam and weir

Velocity(m/s) profiles at 60 seconds are shown below -



(a) (b)

Fig.3.1.4– Velocity(m/s) profile at 60sec (a) without dam and weir (b) with rectangular dam and weir



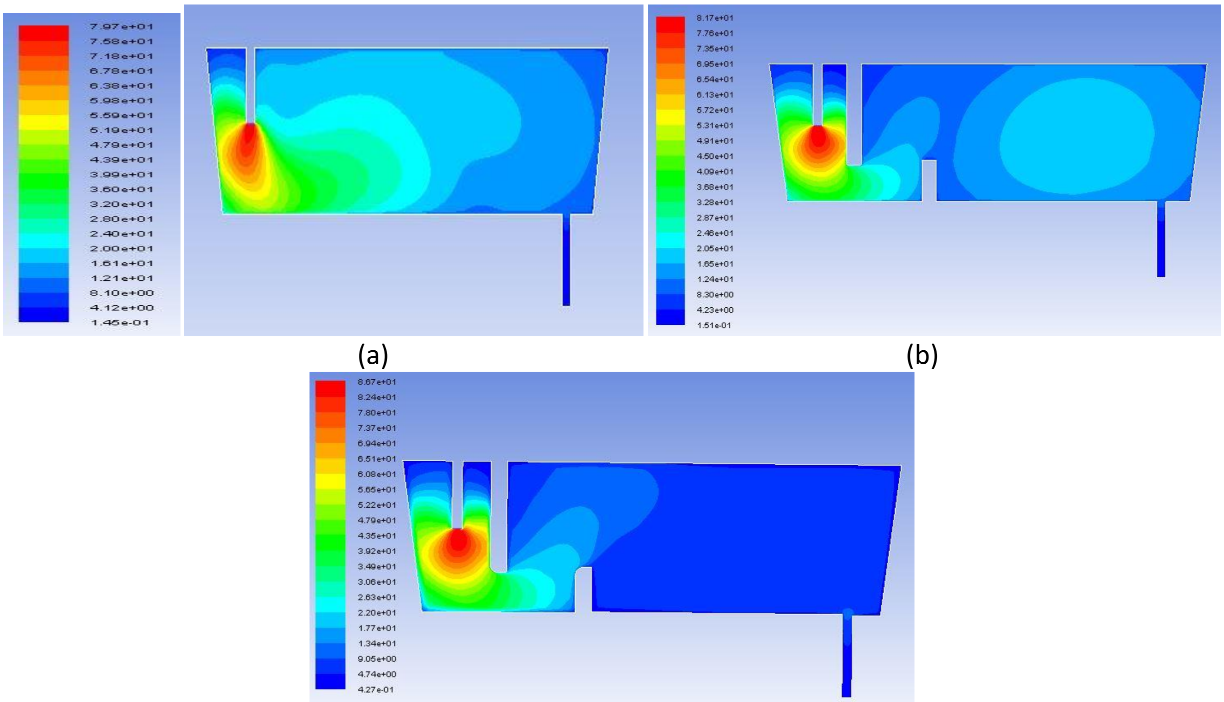
(a) (b)

Fig.3.1.5 – Velocity(m/s) profile at 60sec with rectangular dam and weir (b) with curve dam and weir

Velocity(m/s) profile shows the floatation of the liquid steel and the inclusion. From the figure shown above it can be seen that flow control devices i.e. dam and weir deviate the path of the flow and also it reduces the intensity of Velocity(m/s). Figure 3.2.3 (a) and (b) compares the shape of dam i.e. a rectangular dam and a curve dam and it can be seen that the rectangular dam provides the more inclination to the liquid steel than the curve dam

- **<u>Turbulent intensity profile-</u>**

The turbulent profiles at 30 sec were shown

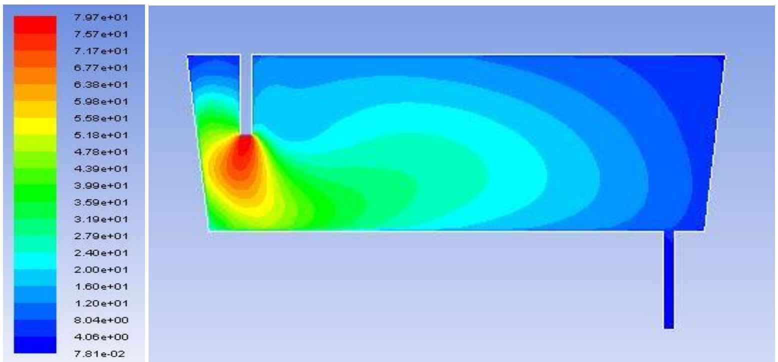


(a) (b)

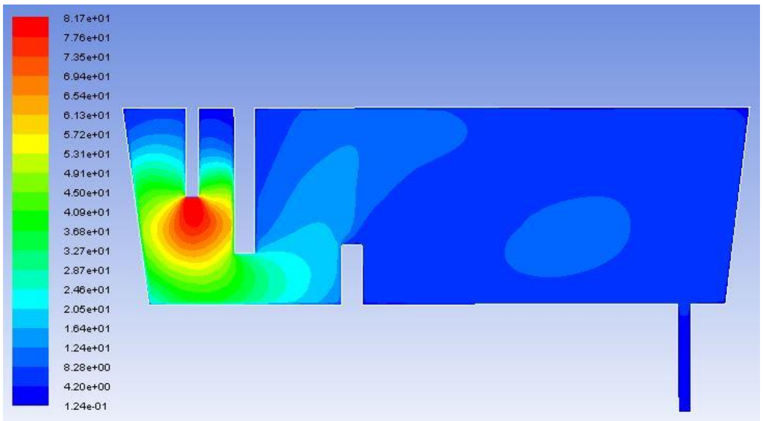
(c)

Fig. 3.1.6 Showing turbulent intensity profile at 30 sec (a) without dam and weir (b) with dam and weir (c) with curve dam and weir

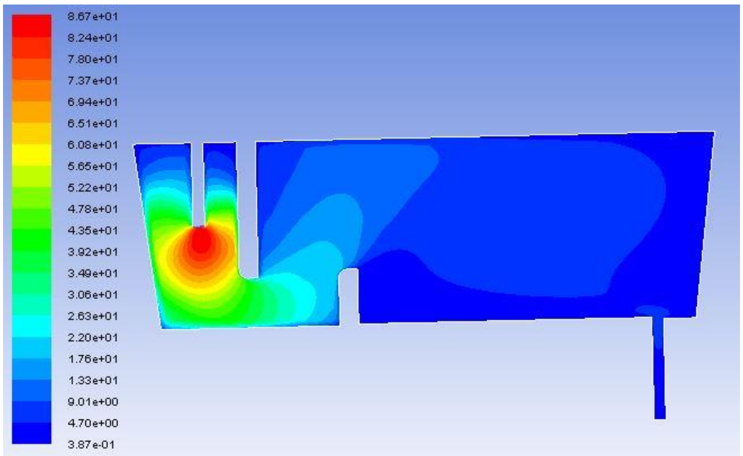
The turbulent profiles at 60 sec were shown below-



(a)



(b)



(c)

Fig.3.1.7 –Turbulent intensity profile at 60 sec (a) without dam and weir (b) with dam and weir (c) with curve dam and weir

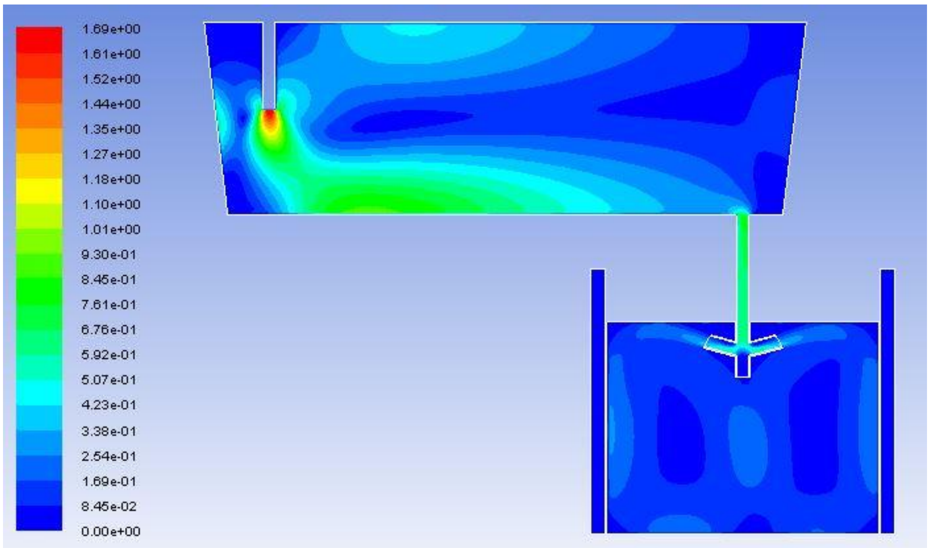
From the above figure it can be seen that dam and weir reduces the turbulence near the SEN and it also prevents the SEN clogging and increases the SEN life.

3.2.1 Steady state cases

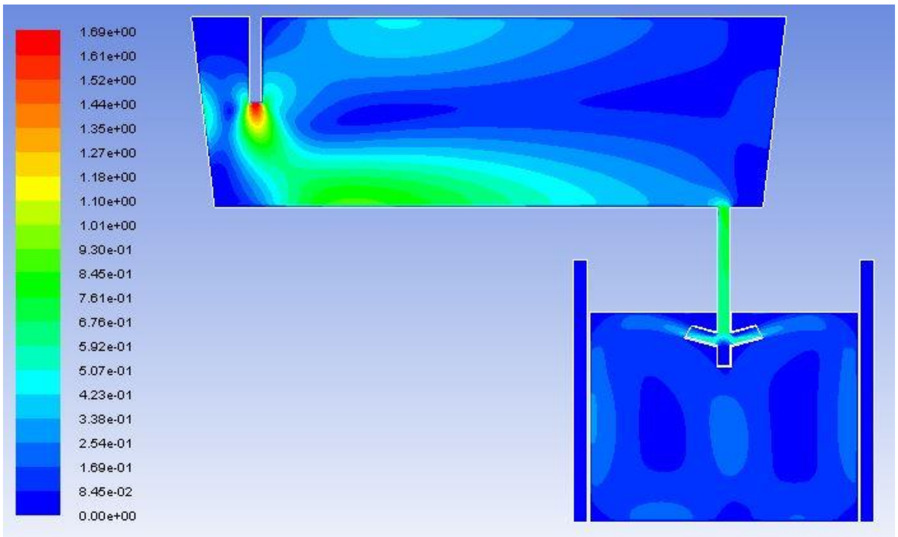
- ❖ Steady state tundish with mould is run and the solution converged at 90000 iterations.
- ❖ Profiles shown are Velocity(m/s) and turbulent intensity
- ❖ Profiles are shown at 45000 sec and 9000 sec

Velocity(m/s) profile-

a. At 45000 sec



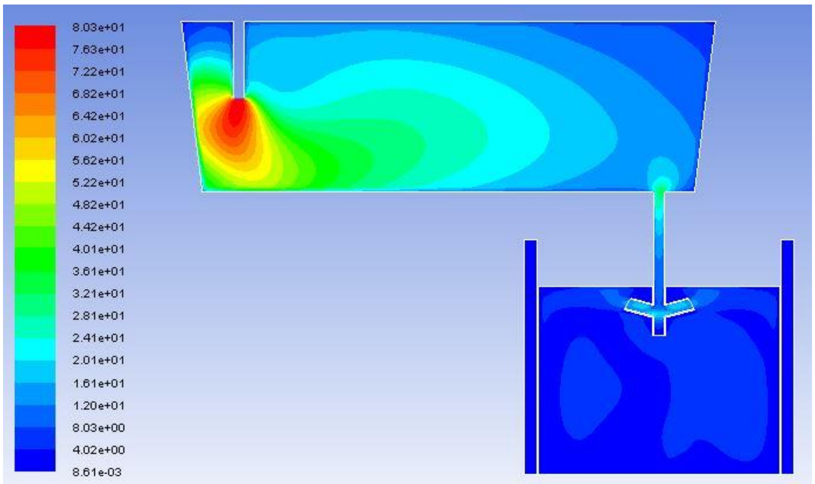
(a)



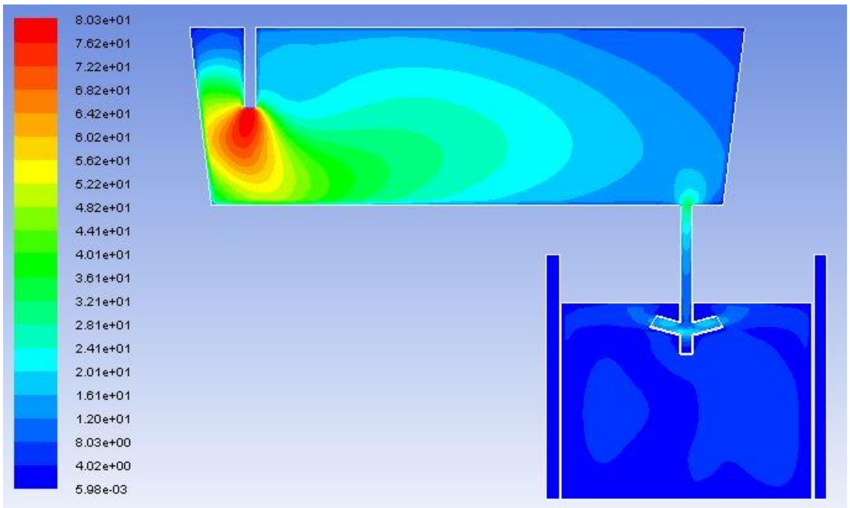
(b)

Figure 3.2.1 Velocity(m/s) profiles (a) at 45000 sec and (b) at 90000 sec

<u>Turbulent intensity profiles</u>-



(a)



(b)

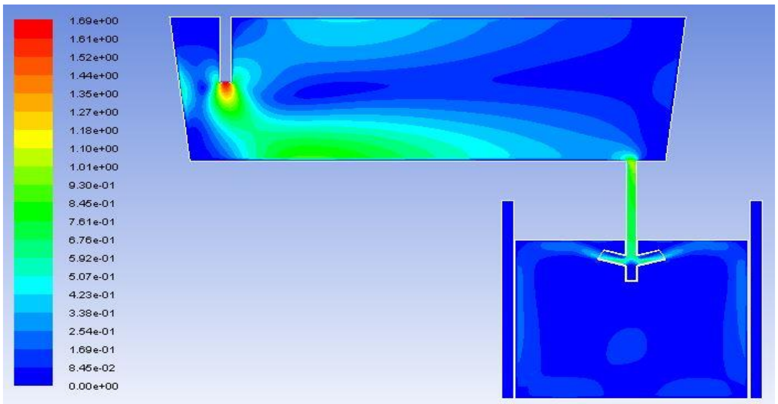
Figure 3.2.2 –Turbulent intensity profile at (a) 45000 sec (b) 90000 sec

The steady state cases are run to check the solution stability and from the above figure it can be seen that the Velocity(m/s) and turbulent intensity profiles does not change after 45000 and 90000 seconds

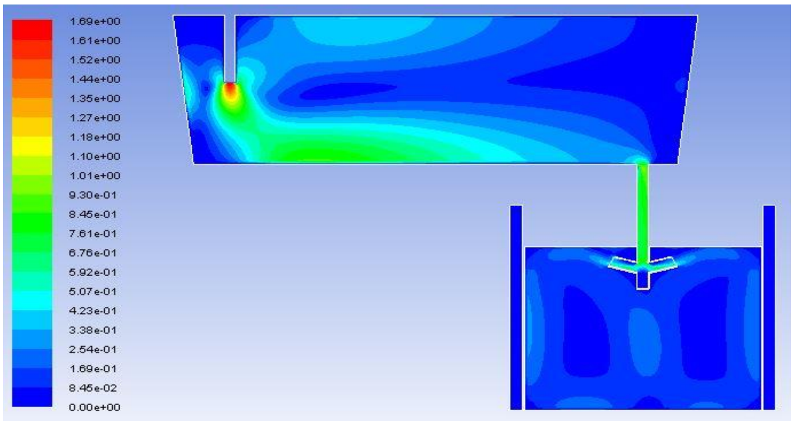
3.2.2 **Transient state –**

- Transient case are run for 1 min with and without dam and weir
- Velocity(m/s) and turbulent intensity profiles at 30sec and 90sec are shown and compare.

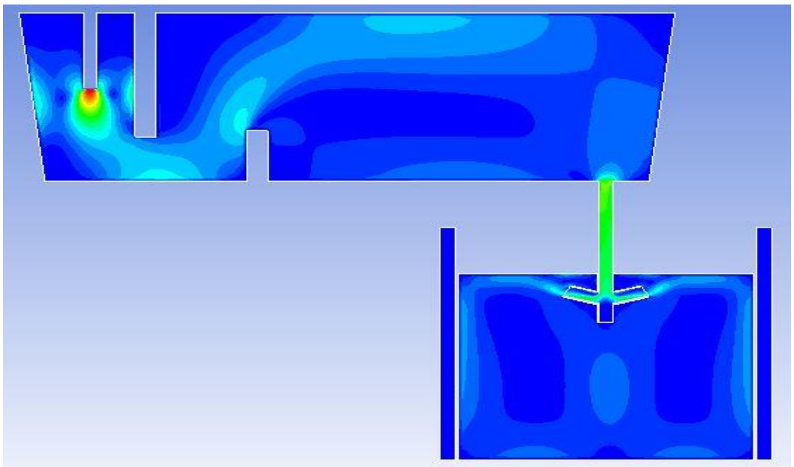
Velocity(m/s) profiles



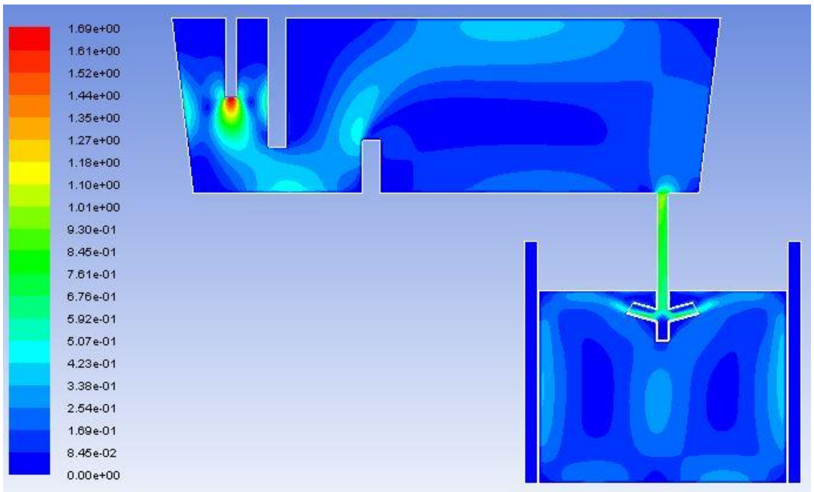
(a)



(b)



(c)

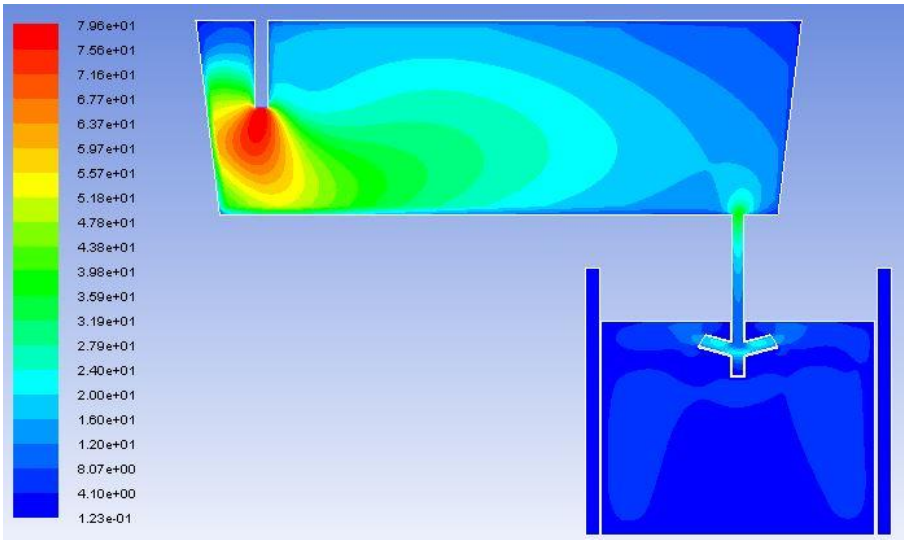


(d)

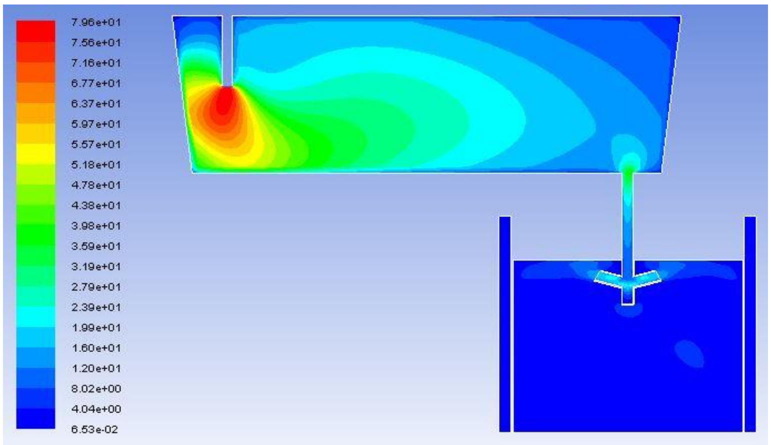
Figure 3.2.3 -Velocity(m/s) profiles without dam and weir (a) at 30 sec (b) at 60 sec (c) and with dam and weir (a) at 30 sec (b) at 60 sec

From the figure shown above it can be seen that the dam and weir does not effect the Velocity(m/s) of the liquid material they only deviate the Velocity(m/s) i.e. they changes the path of the Velocity(m/s) as it can be seen that Velocity(m/s) in the nozzle is same with and without dam and weir, so dam and weir provides floatation to the liquid steel.

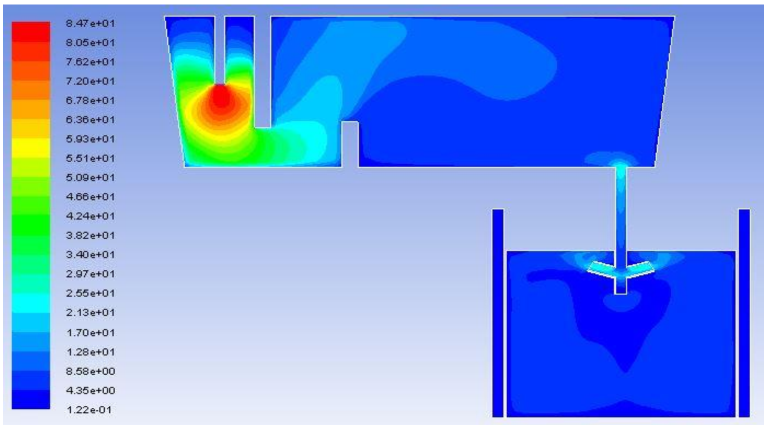
Turbulent intensity profile



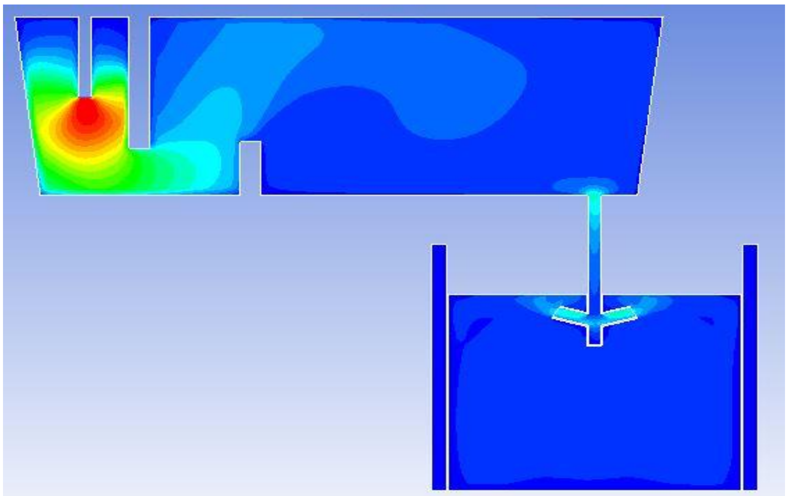
(a)



(b)



(b)



(d)

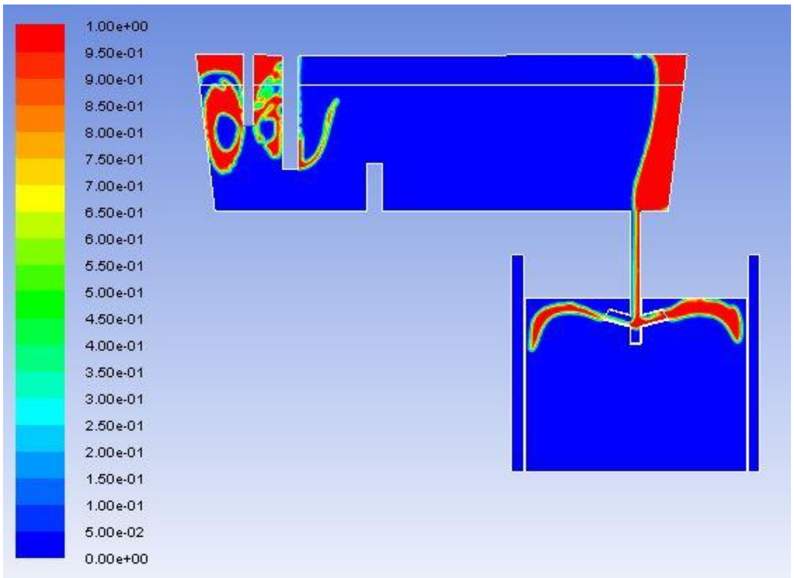
Figure 3.2.4 –turbulent intensity profiles without dam and weir (a) at 30 sec (b) at 60 sec (c) and with dam and weir (a) at 30 sec (b) at 60 sec

The dam and weir reduces the turbulent intensity near the SEN area which can been seen from the above figure

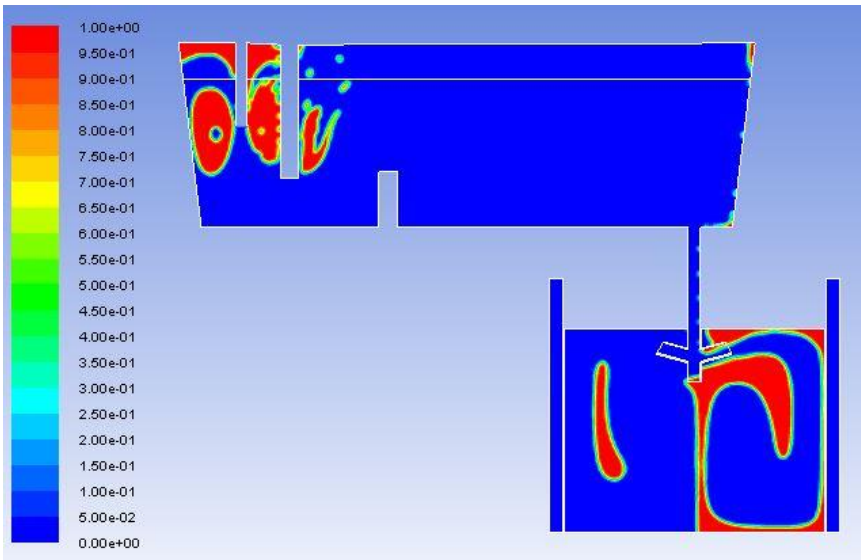
3.3 Two Phase-

A 2D two phase with tundish including mould, dam and weir is run as slag being the 1st phase and liquid steel being the 2nd phase in transient case. The result shown below

- **Slag profile**



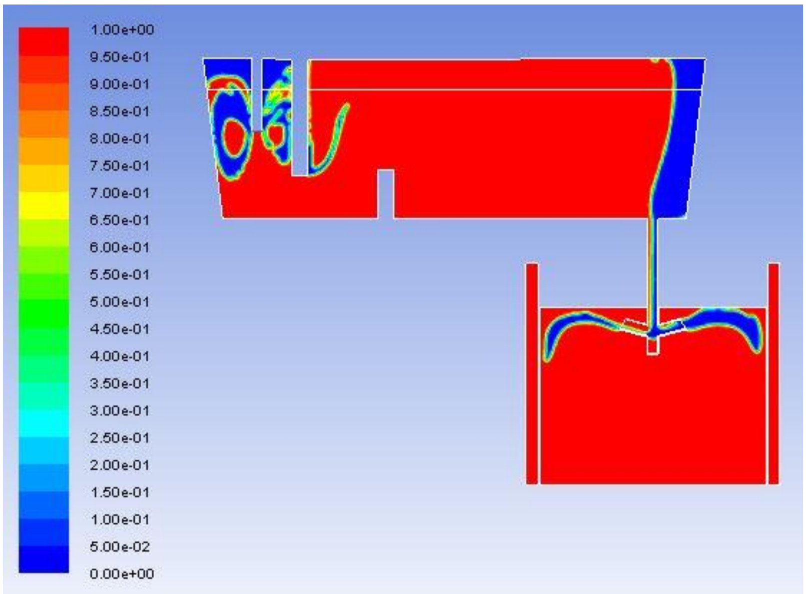
(a)



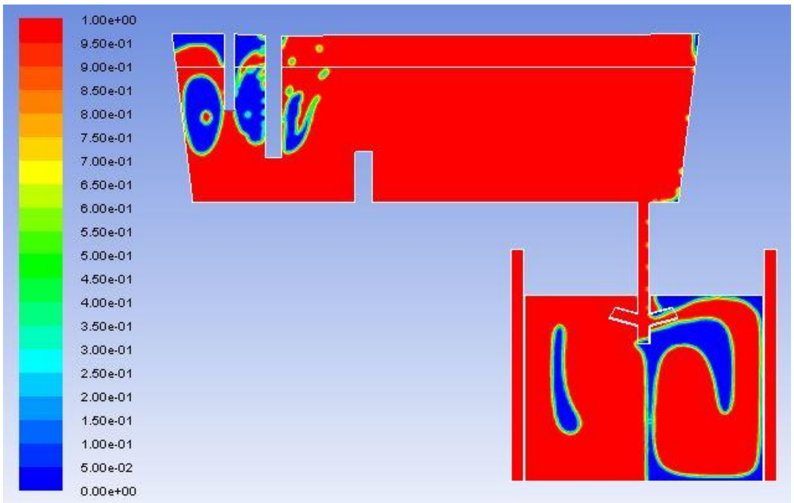
(b)

Figure 3.3.1- Shows the slag profile of the two phases (a) 30 sec and (b) 60 sec

- **Liquid steel**



(a)



(b)

Figure 3.3.2- Shows the liquid steel profile of the two phases (a) 30 sec and (b) 60 sec

From the above figure it can be seen that the slag is entering in the mould region and from the literature review study (10-15) % inclusion can be removed from the mould by using the casting powder which is sprayed on the mold which attracts the slag which can be seen from the figure.

3.4. DPM MODAL-

- DPM stands for discrete phase modeling which tracks the motion of individual (discrete) particles.
- Some principles are applied whether a particle is a solid particle or liquid particles
- Trajectory of each particle(droplet) is computed over a large number of steps
- A massless particle is injected from the surface of the inlet and the trajectory and the residence time is calculated on the same basis.

1. Different Cases run with DPM modal are –

A. Single phase

1. Only tundish

a. Steady state tundish
b. Transient state tundish
c. Transient case tundish with dam and weir

2. Tundish with mold

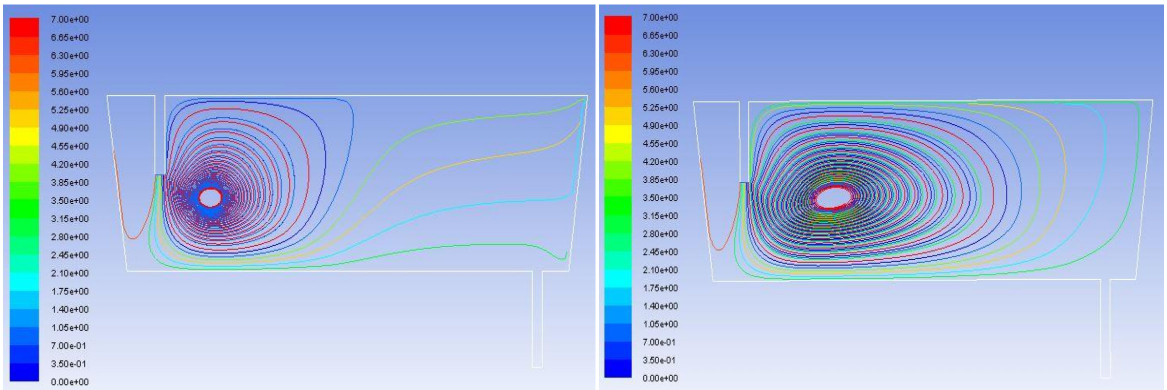
a. Steady state tundish with mould
b. Transient case tundish with mould
c. Transient case tundish with dam and weir and with mould

B. Two phase

a. Transient case tundish and mould, dam and weir

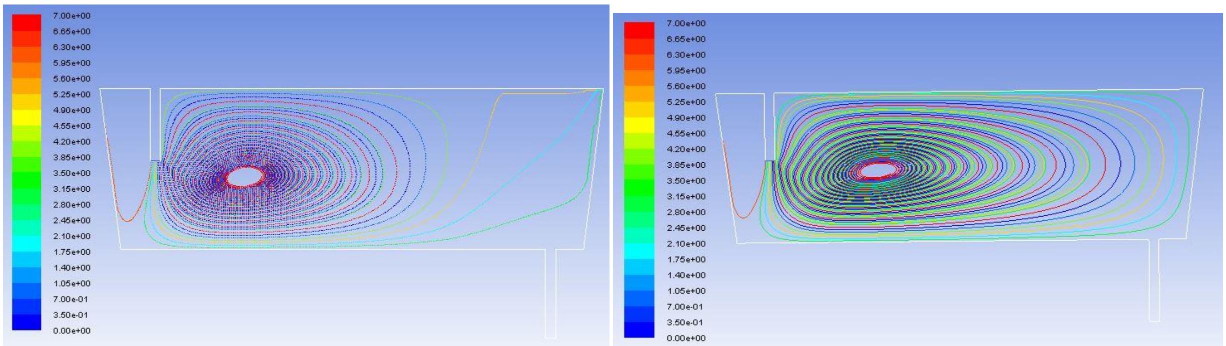
3.4.1 Single phase

A. Only tundish



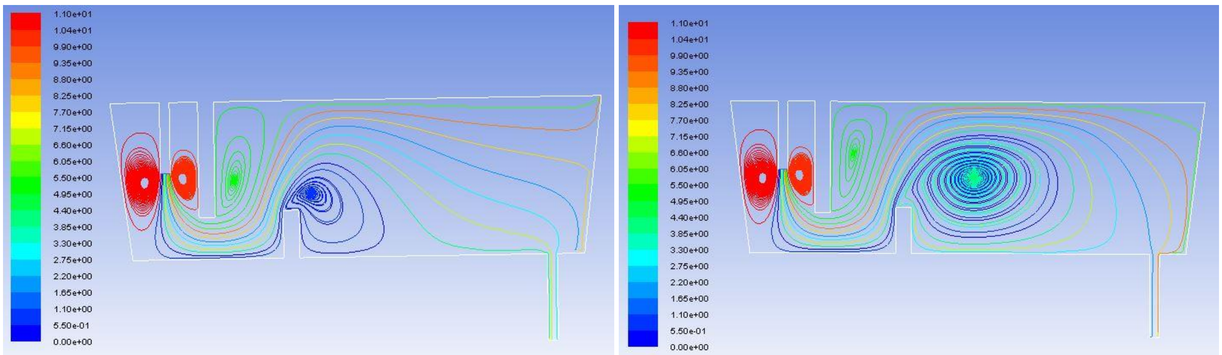
(a) (b)

Figure 3.4.1 – particle tracking without dam and weir (a) at 1500 sec (b) at 3000 sec in steady state



(a) (b)

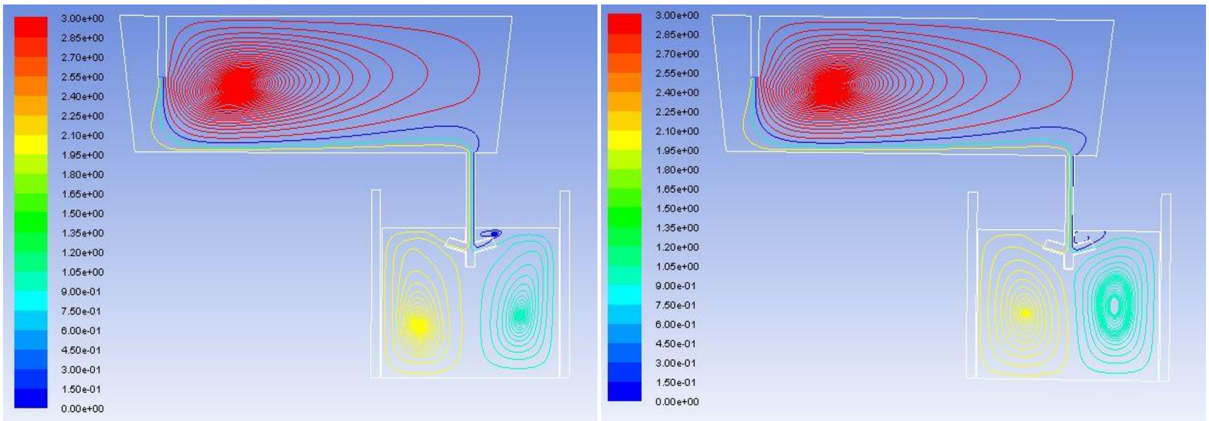
Figure 3.4.2 – particle tracking without dam and weir (a) at 30 sec (b) at 60 sec in transient state



(a) (b)

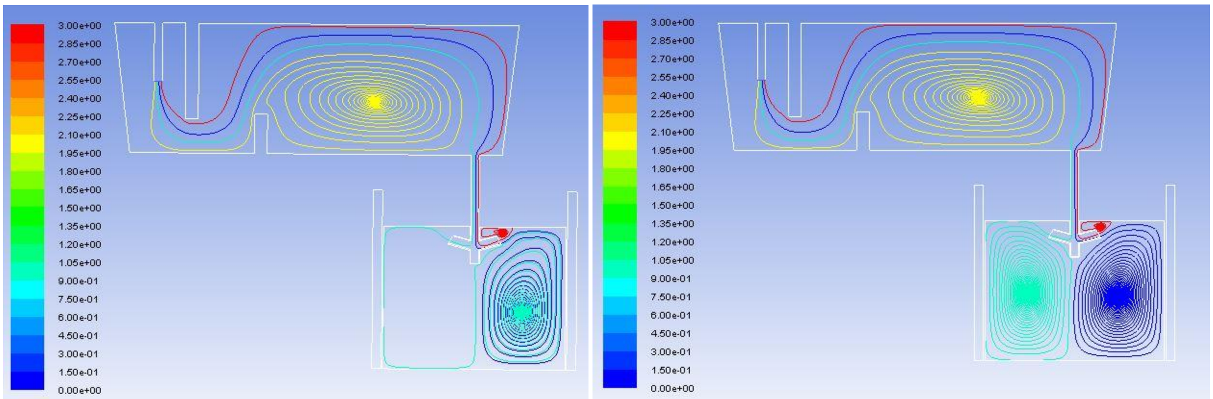
Figure 3.4.3 – particle tracking with dam and weir (a) at 30 sec (b) at 60 sec in transient state

B. Tundish with mold



(a) (b)

Figure 3.4.4 – particle tracking without dam and weir (a) at 30 sec (b) at 60 sec in transient state



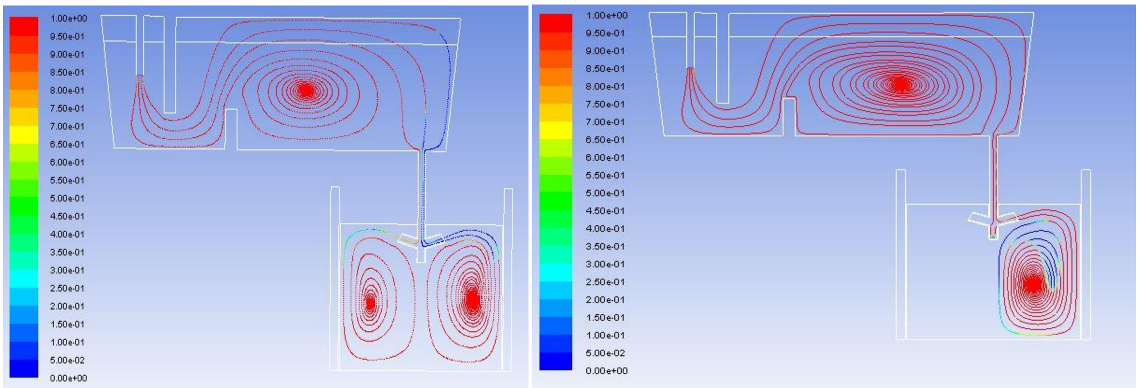
(a) (b)

Figure 3.4.5 – particle tracking with dam and weir (a) at 30 sec (b) at 60 sec in transient state

From the particle trajectory it can be seen that the recirculation zone is less with dam and weir then without dam and weir and also the dam and weir provides enough time for the bubble particle to float and can be extracted by the slag

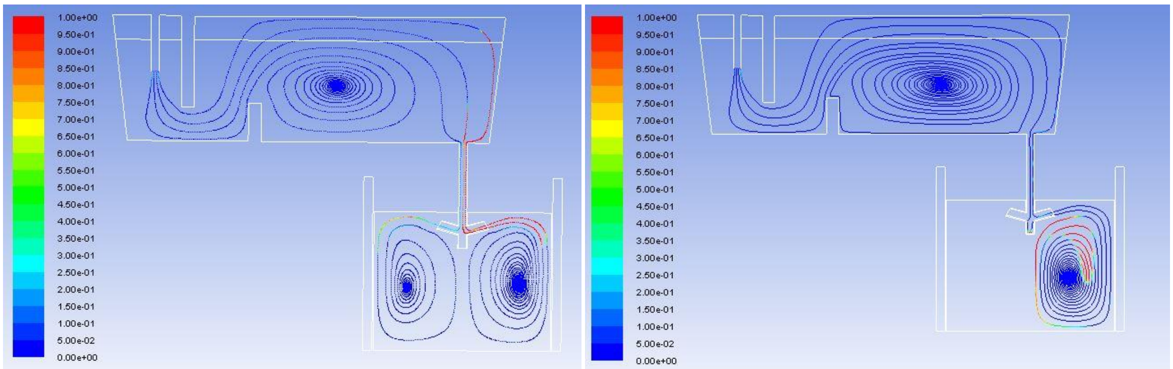
3.4.2 Two phase

a. Transient case tundish with mould dam and weir



(a) (b)

Fig.3.4.6- particle tracking of the hot metal (a) at 30sec and (b) at 60 sec



(a) (b)

Fig.3.4.7- particle tracking of the slag metal (a) at 30sec and (b) at 60 sec

3.5 Residence time

Residence time is the time taken by the liquid metal to flow from tundish to mold. If the residence time is less then inclusion will not have the enough time to float and they can be trapped and can go into the mold which detroits the properties of the solidified. A massless particle is injected from the inlet of the tundish and the residence time is calculated only for the tundish which is shown in the table 3.7 below.

Table3.6- calculated residence time

Cases	Time
Without dam and weir	31 sec
With curve dam and weir	68 sec
With rectangular dam and weir	120 sec

So from the residence time calculated it can be said that the flow control devices increases the residence time so the inclusion can float and can come up on the surface of the tundish where they can be taken out from the slag.

Part 3.6 Temperature variation in slab

A temperature profile with radiation and with both radiation and the convection was calculated as there is a crack problem at edges of strip in Jindal, hisar and the temperature profile was calculated in order to understand the difference of temperature between surface of the strip and narrow edge/face so as to optimize % reduction in pass schedule in finishing stands.

With radiation only-

The temperature calculated from the model with radiation only is shown below in table 3.7

Table 3.7 – Calculated Temperature in C from the CFD model

Time(sec)	25mm	28mm	30mm
10	1021.743	1024.972	1028.34
20	976.248	1002.32	990.586
30	937.005	948.502	956.214
40	901.873	916.607	926.191

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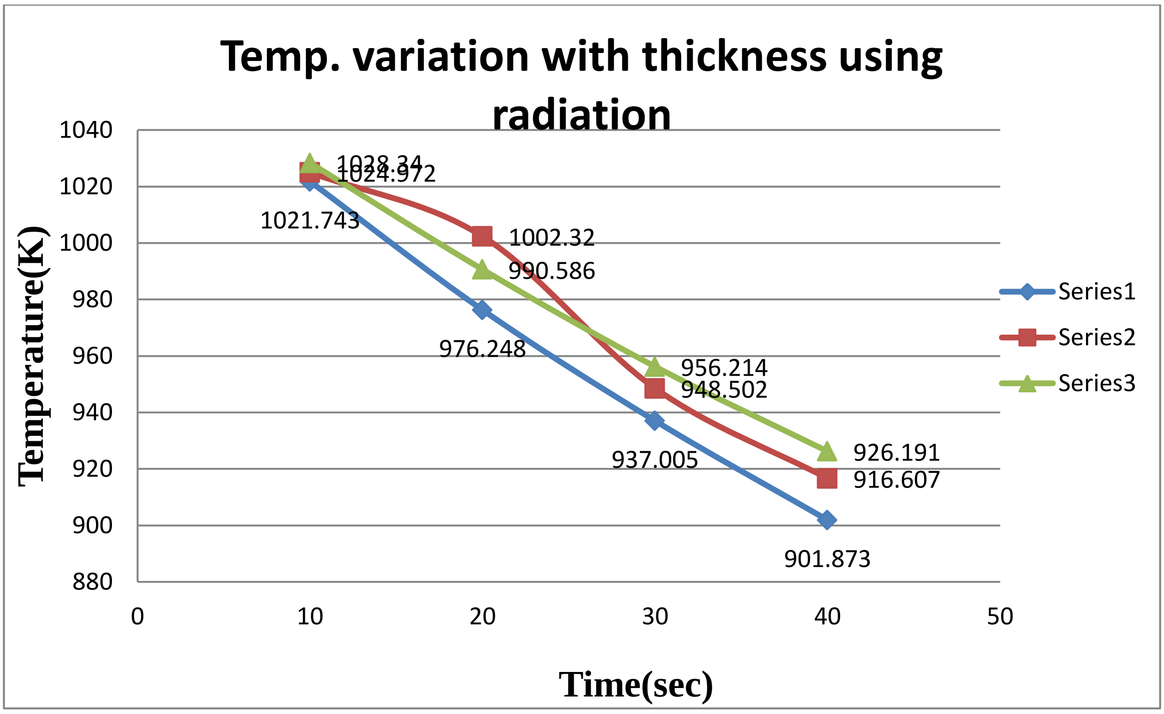

Figure 3.6.1 variation of temp. with radiation only

With radiation and convection only-

The temperature calculated from the model with radiation and convection is shown below in table 3.8

Table 3.8 – Calculated Temperature in C from the CFD model

Time(sec)	25mm	28mm	30mm
10	1004.995	1009.152	1013.57
20	945.698	956.948	963.145
30	894.6155	910.948	918.7735
40	849.848	868.835	880.1925

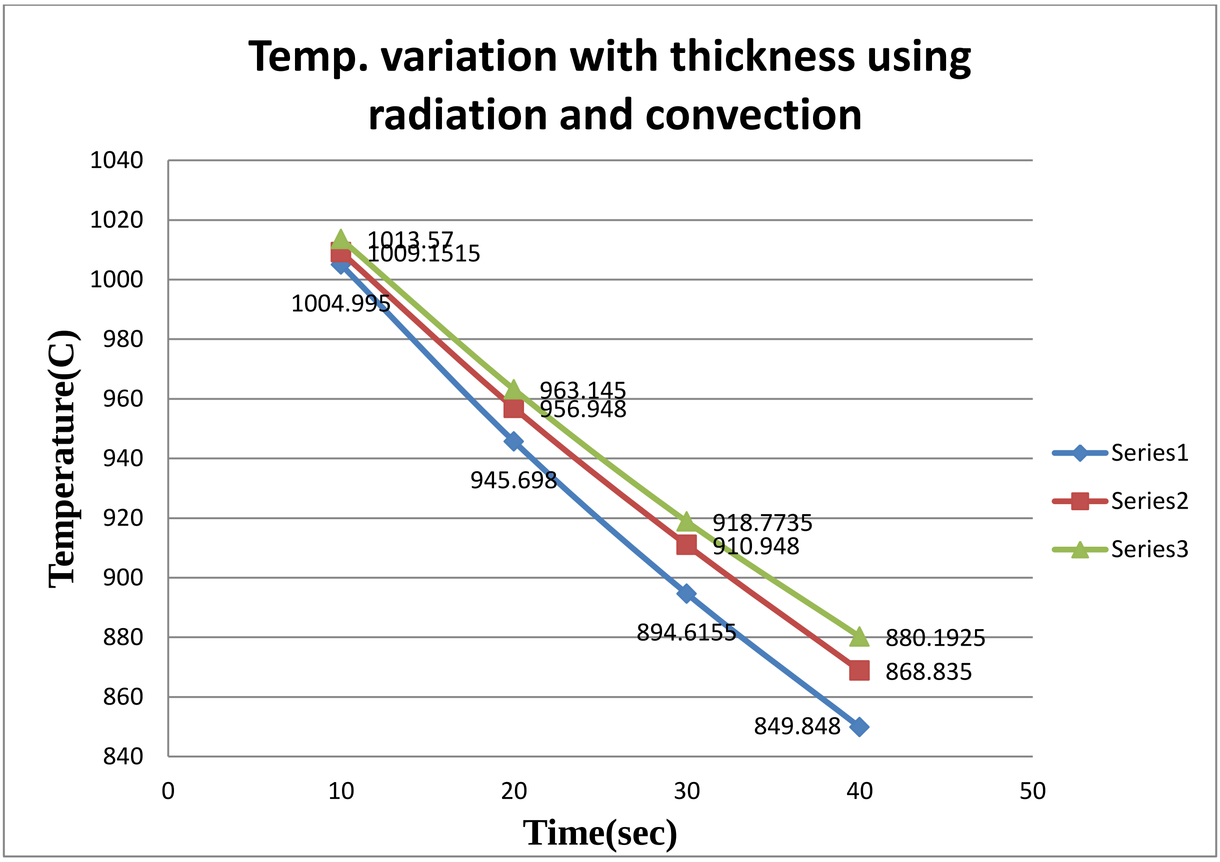

Figure 3.6.2 variation of temperature with radiation and convection

From the model using radiation and with radiation and convection both, the temperatures were calculated from the temperature profiles and with the increase in strip thickness the temperature decreases so on the basis of this and the calculated temperature the strip thickness is optimized and it shows that the cracks are reduced by 25% as previously, cracks was 100 mm (total 200 mm) both side of the strip. After modification of percentage reduction the edge cracks reduces to ~25 mm both side (Total 50 mm). This was done in 2 coils.

<u>*Chapter- 4*</u>

Conclusion

4. Conclusion

A computational fluid dynamic (CFD) study is conceded on the continuous casting process to achieve the desired objective. A Standard turbulent k-ε model is used for the CFD analysis. In this simulation, a tundish with and without the rectangular and a curve dam and weir are used for the simulation and on the basis of calculated residence time from the DPM model by injecting a massless particle it was concluded that the rectangular Dam and Weir is the most effective in reducing the turbulence at the SEN side. A two phase model is also studied and the slag profile is shown in the result and discussion which shows the use of casting powder in the mold. The strip temperature is calculated using the radiation first and in the second both radiation and convection as the training project in the Jindal and on the basis of the results the strip thickness is modified which shows that there is 25 percent reduction in the crack, so on this basis it can be said that mathematical model is very good at predicting flow behavior and the temperature profile and consequently the crack generation possibility in casted slab and can be applied to industries.

Chapter- 5

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